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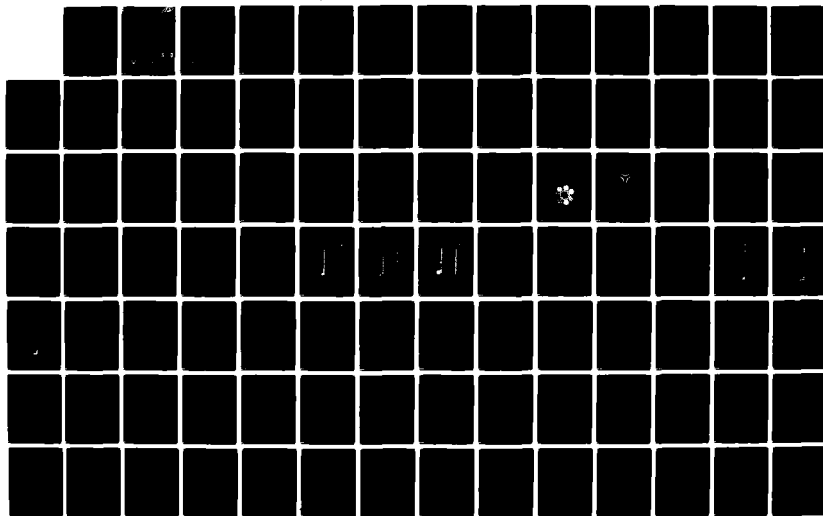
ANALYSIS OF THE LARGE URBAN FIRE ENVIRONMENT PART II
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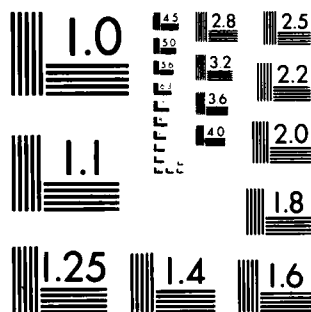
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PSR Report 1210

ANALYSIS OF THE LARGE URBAN FIRE ENVIRONMENT

Part II. Parametric Analysis and Model City Simulations

By
D. A. Larson
R. D. Small

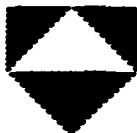
November 1982

Final Report
Contract EMW-C-0747, Work Unit 2564E

For
Federal Emergency Management Agency
National Preparedness Programs
Washington, D.C. 20472

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BLOCK 20 (cont.)

burning rate is increased. A sample calculation illustrates the change in fire-wind velocities as the fire evolves over time.

Calculations of the burning region for three model urban areas show the influence of building density and urban sprawl on the resulting fire environment. An additional set of predictions accounts for reduction of the fire intensity by blast in the urban center. For the latter cases, the temperature distribution is changed markedly, though the magnitude of the induced fire winds is not appreciably reduced.

PREFACE

This report is the second of the two-part documentation of Pacific-Sierra Research Corporation's analysis of the large urban fire environment. This part presents calculations of the characteristics of nuclear-weapon-ignited fires. Part I develops the theory underlying the analysis. All work was performed for the Federal Emergency Management Agency under contract EMW-C-0747; the technical monitor was Dr. David Bensen.

The authors gratefully acknowledge the contributions of Dr. Harold L. Brode.

SUMMARY

This report considers the large-fire environment that would occur in an urban area subject to a nuclear weapon explosion. The effects of system parameters are explored in a sensitivity study, and results for three model cities are presented.

The examples are characterized by extensive areas simultaneously burning, strong buoyancy, and large temperature gradients. Several such fires occurred during World War II. Though those fires were dramatic in intensity and destructiveness, each involved a relatively small area. A nuclear weapon explosion could generate a far larger area fire and a more severe fire environment. This report is intended to define such large fires. The results should be applicable for damage evaluation, formulation of shelter requirements, and rescue planning.

The calculations are based on the theory developed in Part I of this report, which is applicable to the fire zone and the volume immediately above it (turning region). The effects of variable area heating, turbulence, strong buoyancy, large temperature changes, and radiation are treated. The induced fire winds and rapid temperature changes at the fire periphery are uniquely determined by the use of jump conditions. Simulations of the Hamburg firestorm and a large Flambeau fire agreed well with available data.

The parametric analysis considers a large area fire and the effects of fire size, heating rates, mixing coefficients, and hot gas/smoke radiation. The results show the influence of those variables on the induced fire winds, mean temperature, and pressure gradients. In general, an increase in either the fire size or heating rate raises the mean temperature levels and the induced fire-wind velocities. For the larger heat release rates or fire sizes, the attendant increases in mean temperature and velocity are limited by compressibility effects.

Fires such as may result from a megaton-yield explosion are analyzed for three model urban areas. Each city is characterized by

a high-density center, a surrounding belt of mixed residential/ industrial construction, and a lower density suburban belt. Each model city portrays a different degree of building density and urban sprawl. The results illustrate how a particular city geometry affects the velocity and temperature fields for a given fire. An additional series of computations considers reduction of the fire area by severe blast damage and debris formation. For those calculations, complete burning was allowed in an annular area, with the fire intensity significantly reduced in the center.

Finally, the model is employed to estimate the behavior of the velocity and temperature fields as a function of fire evolution. Those calculations may indicate the most appropriate periods for effecting rescue operations as well as provide an estimate of time-dependent shelter loadings.

CONTENTS

PREFACE	iii
SUMMARY	v
FIGURES	ix
TABLES	xiii
SYMBOLS	xv
Section	
I. INTRODUCTION	1
II. PARAMETRIC ANALYSIS OF LARGE-FIRE ENVIRONMENT	5
Baseline analysis	6
Dependence on fire size and burning rate scale ..	11
Dependence on burning rate spatial distribution .	16
Dependence on turbulence and radiation	22
III. MODEL CITY ANALYSIS	28
Definition	28
Simulation results	36
IV. SAMPLE TIME-DEPENDENT SIMULATION	56
V. DISCUSSION	64
APPENDIX: PREDICTION-ALGORITHM DOCUMENTATION	67
REFERENCES	119

FIGURES

1. Velocity field for baseline fire	8
2. Temperature contours for baseline fire	9
3. Pressure contours for baseline fire	9
4. Radial velocity profiles for baseline fire	10
5. Vertical velocity profiles for baseline fire	10
6. Dependence of maximum radial velocity and temperature on fire radius	13
7. Dependence of maximum radial velocity and temperature on burning rate scale	13
8. Dependence of maximum radial velocity and temperature on fire height	14
9. Dependence of maximum perturbation pressure and verti- cal velocity on fire radius	15
10. Dependence of maximum perturbation pressure and verti- cal velocity on burning rate scale	15
11. Dependence of maximum perturbation pressure and verti- cal velocity on fire height	16
12. Temperature contours of baseline and annular fires	18
13. Flow fields of baseline and annular fires	19
14. Radial airflow and fire spread patterns suggested for annular cluster of large area fires	20
15. Radial airflow and fire spread patterns suggested for cluster of three large area fires	21
16. Dependence of maximum radial velocity and temperature on eddy coefficient for momentum transfer	23
17. Dependence of maximum radial velocity and temperature on eddy coefficient for heat transfer	23
18. Dependence of maximum radial velocity and temperature on eddy coefficients	24
19. Dependence of maximum radial velocity and temperature on radiation mean free path	24

20. Dependence of maximum perturbation pressure and vertical velocity on eddy coefficient for momentum transfer	25
21. Dependence of maximum perturbation pressure and vertical velocity on eddy coefficient for heat transfer ..	25
22. Dependence of maximum perturbation pressure and vertical velocity on eddy coefficients	26
23. Dependence of maximum perturbation pressure and vertical velocity on radiation mean free path	26
24. Fire schematic for baseline and blast-modified city W .	30
25. Fire schematic for baseline and blast-modified city M .	31
26. Fire schematic for baseline and blast-modified city E .	32
27. Baseline and blast-modified heating rate spatial distributions for city W	37
28. Baseline and blast-modified heating rate spatial distributions for city M	38
29. Baseline and blast-modified heating rate spatial distributions for city E	39
30. Typical velocity field in model city simulations	42
31. Baseline and blast-modified temperature contours for city W	43
32. Baseline and blast-modified pressure contours for city W	44
33. Baseline and blast-modified radial velocity profiles for city W	45
34. Baseline and blast-modified vertical velocity profiles for city W	46
35. Baseline and blast-modified temperature contours for city M	47
36. Baseline and blast-modified pressure contours for city M	48
37. Baseline and blast-modified radial velocity profiles for city M	49
38. Baseline and blast-modified vertical velocity profiles for city M	50

39. Baseline and blast-modified temperature contours for city E	51
40. Baseline and blast-modified pressure contours for city E	52
41. Baseline and blast-modified radial velocity profiles for city E	53
42. Baseline and blast-modified vertical velocity profiles for city E	54
43. Areal heat release time-history for Flambeau fire 760-12	56
44. Time-history of maximum and minimum combustion zone temperatures for sample Flambeau fire	59
45. Time-history of peripheral pressure drop for sample Flambeau fire	59
46. Time-history of induced peripheral fire wind (radial velocity) for sample Flambeau fire	60
47. Time-history of emerging column flow (vertical velocity at top of turning region) for sample Flambeau fire ..	60
48. Temperature contours after 15 min for sample Flambeau fire	62
49. Pressure contours after 15 min for sample Flambeau fire	62
50. Radial velocity profiles after 15 min for sample Flambeau fire	63
51. Vertical velocity profiles after 15 min for sample Flambeau fire	63
A.1. Flow chart of prediction algorithm for turning-region boundary value problem	69
A.2. Flow chart of main program	75
A.3. Finite difference grid and stencils for numerical solution of turning-region problem	77
A.4. Flow chart of subroutine MSWEEP	80
A.5. Flow chart of Newton steps used in subroutine MSWEEP ..	81

TABLES

1. Parameter dependence on fire radius	12
2. Parameter dependence on fire height	12
3. Parameter dependence on burning rate scale	12
4. Velocity, temperature, and perturbation pressure maxima for various burning rates	17
5. Velocity, temperature, and perturbation pressure maxima for baseline and uniform fires	22
6. Size and density of model city regions	29
7. Fuel loading in model city regions	33
8. Parameters in model city simulations	35
9. Velocity, temperature, and perturbation pressure maxima in model city simulations	40
10. Heat release scales used in time-dependent Flambeau simulation	58
A.1. Sample code output	72
A.2. Listing of main program	102
A.3. Listing of subroutine BCFUNC	106
A.4. Listing of subroutine SPRINT	109
A.5. Listing of subroutine MSWEEP	111

SYMBOLS

MATHEMATICAL SYMBOLS

- A = dimensionless constant, gH/U^2
- c_p = specific heat capacity at constant pressure
- E_B = average heat released per unit weight of all combustibles
- ζ_1 = effective kinematic viscosity (for turbulent flow)
- f_{Bu} = building density (ratio of area covered by buildings to total area)
- F = dimensionless measure of QH [defined by Eq. (13)]
- g = gravitational acceleration
- H = maximum height of flames
- k^* = reciprocal of graybody radiation mean free path
- k_1 = effective thermal conductivity (for turbulent flow)
- K_1 = dimensionless heat-diffusion coefficient
- L_s = average fuel loading per building story
- L_T = average areal fuel loading
- M_1 = dimensionless momentum-diffusion coefficient
- N_s = average number of building stories
- P = perturbation pressure (dimensionless)
- P_a = ground-level atmospheric pressure in far field
- P_{max} = maximum perturbation pressure
- q = dimensionless spatial distribution of volumetric heat-addition rate
- Q = volumetric heat-addition-rate scale
- Q_A = areal heat-addition rate

r = radial position coordinate (dimensionless, except in Figs. 24 through 26)
 R = fire radius
 T = temperature (dimensionless)
 T_a = ground-level atmospheric temperature in far field
 T_{\max} = maximum temperature
 u = radial velocity (dimensionless)
 u_{\max} = maximum radial velocity
 U = radial velocity scale
 v = vertical velocity (dimensionless)
 v_{\max} = maximum vertical velocity
 y = vertical position coordinate (dimensionless)
 γ = specific heat ratio
 δ = dimensionless constant, $U^2 / (P_a / \rho_a)$
 ϕ = radial dependence of model-city heat release rates in blast-modified cases
 ρ = density (dimensionless)
 ρ_a = ground-level atmospheric density in far field
 $\sigma = \frac{4\pi\hat{\sigma}T_a^4 k^*}{Q}$ = radiation coefficient (dimensionless constant),
 $\hat{\sigma}$ = Stefan's constant

SYMBOLS[†] USED IN DOCUMENTATION OF PREDICTION ALGORITHM

E_j = intermediate variable [defined by Eq. (A.37)]
 $\vec{F}, \vec{G}, \vec{H}$ = vectors of functions that are to be driven to zero (by proper choice of \vec{x}) in Newton iterations, and that represent discretized model equations on individual lines of constant y

[†]Mathematical variables only--not FORTRAN labels.

- G_i, H_i = i th components of \vec{G} and \vec{H}
- i = radial position index ($1 \leq i \leq M + 1$)
- j = vertical position index ($1 \leq j \leq N + 1$)
- $J = \partial \vec{F} / \partial \vec{x}$ Jacobian matrix
- k = vector component index ($1 \leq k \leq 2M$)
- ℓ = index for $\alpha, \beta, \gamma, \delta$ Jacobian elements ($1 \leq \ell \leq M$)
- m, n = iteration counters in Newton and shooting iterations
- M, N = number of finite difference cells in radial and vertical directions, respectively (see footnote, p. 68)
- p = index for $\alpha, \beta, \gamma, \delta$ Jacobian elements ($0 \leq p \leq 2$)
- $P_{i,j} = P(r_i, y_j)$
- P_{old}, P_{new} = successive discretized forms of P in shooting iterations
- $(Qq)_{max}$ = maximum value of Qq
- $r_i = (i - 1) \Delta r$
- R_i = sum of all terms in G_i , for any line $y = y_j$, j fixed, that depend only on $y = y_{j-1}$ data
- t = time
- \vec{T} = vector of discrete T values for line of constant y
- $T_{i,j} = T(r_i, y_j)$
- T_{old}, T_{new} = successive discretized forms of T in shooting iterations
- \vec{u} = vector of discrete u values for line of constant y
- $u_{i,j} = u(r_i, y_j)$
- u_{old}, u_{new} = successive discretized forms of u in shooting iterations
- $v_{i,j} = v(r_i, y_j)$
- w = generic variable
- $w_{i,j}$ = generic finite-difference variable

\vec{x} = vector of discrete u and T values for line of constant y

\tilde{x}_k = k th component of \vec{x}

$\vec{x}_{old}, \vec{x}_{new}$ = successive discretized forms of \vec{x} in Newton iterations

$y_j = (j - 1) \Delta y$ for $j \leq 5M + 1$; $5 + (j - 5M - 1)(2 \Delta r)$ for $j > 5M + 1$

y_{max} = maximum value of y considered

$\alpha_{p,l}$ = nonzero element in $\partial \vec{G} / \partial \vec{u}$ Jacobian ($0 \leq p \leq 2, 1 \leq l \leq M$)

$\beta_{p,l}$ = nonzero element in $\partial \vec{G} / \partial \vec{T}$ Jacobian ($0 \leq p \leq 2, 1 \leq l \leq M$)

$\gamma_{p,l}$ = nonzero element in $\partial \vec{H} / \partial \vec{u}$ Jacobian ($0 \leq p \leq 2, 1 \leq l \leq M$)

$\vec{\delta}$ = vector difference between successive values of \vec{x} in Newton iterations

δ_k = k th component of $\vec{\delta}$

$\delta_{p,l}$ = nonzero element in $\partial \vec{H} / \partial \vec{T}$ Jacobian ($0 \leq p \leq 2, 1 \leq l \leq M$)

$\Delta r, \Delta y$ = cell width and height, respectively

Π_i = sum of all terms in H_i , for any line $y = y_j$, j fixed, that depend only on $y = y_{j-1}$ data

$\rho_{i,j} = \rho(r_i, y_j)$

ω = relaxation coefficient in shooting iterations

I. INTRODUCTION

This report presents predictions of the temperatures, pressures, and high-speed winds created by large urban fires. The dependence of those quantities on fire size, burning rate, and various other parameters is explored, and fires in model U.S. cities are examined. Simulations in which nuclear-weapon-ignited fires are extinguished in the center by blast are compared with those in which the fires continue to burn. The model developed in Part I of this report was used to calculate all values. That model may be readily extended to obtain estimates of oxygen depletion and noxious gas buildup as well and, hence, a fairly complete baseline description of the environment facing civil defense personnel when large urban areas are burning.

Most previous research concerning the hydrothermodynamics of free-burning fires has been restricted to the weakly buoyant free-convection plume. The resulting theories describe the basic flow in the middle and upper parts of a long, thin plume over a small fire, and may be relevant to some portion of the convection column generated over a large urban fire [e.g., Morton, Taylor, and Turner, 1956; Murgai and Emmons, 1960; Yokoi, 1960; Nielsen and Tao, 1965]. However, as discussed in Part I, such theories are inapplicable in and around the combustion zone, so they cannot be used to predict the environment and high-speed surface winds induced by large fires.

Smith, Morton, and Leslie [1975] present global computations of the hydrothermodynamic environment near the combustion zone as well as above it. In their calculations, all components of the fire-generated flow field--e.g., surface inflow, the convection column, the far field--are considered collectively, and the strong coupling between dynamic forces and the induced surface winds is demonstrated. In and around the combustion zone, however, density changes are assumed to be small (Boussinesq approximation), heat is input at the boundary rather than in volume, and not much resolution is sought.

Further, the computations are not specifically designed for the analysis of large urban fires.

In a more recent study, Brode, Larson, and Small [1982] adopt the basic computational approach of Smith, Morton, and Leslie in studying the mesoscale motions generated by large fires, but eliminate some of the stated deficiencies. Their work is directly aimed at the definition of the large urban fire environment, and arbitrary changes in temperature and density are allowed in the near-fire region. The resolution in that region is still rather coarse, however.

The component analysis introduced by Small, Larson, and Brode [1981] provides an alternative to the global-calculation analysis in which fine resolution near the fire can be obtained economically. Using that approach, the components of the flow field are analyzed separately, and then combined by means of appropriate matching conditions. The special features of each component are thus considered in greater detail, and resolution is enhanced.

The key element in the component analysis is the description of the environment in and around the fire, since the entire flow is driven by the hydrothermodynamic interactions in that region. The turning-region model developed in Part I provides the key description. That model decouples from those for the other flow components, and thus can be used independently to make detailed predictions of the near-fire environment. Such a capability extends our understanding of fire dynamics and is the basis for the present analysis.

We use the turning-region model to generate the large urban fire predictions. In that model, a volume heat source represents the net effect of the combustion process, and the induced flow is taken to be axisymmetric and quasi-steady. The flow is also assumed compressible, to permit arbitrary changes in temperature and density. A one-parameter eddy-viscosity model is used to describe the turbulent transfer of heat and momentum, and a graybody approximation to model hot gas and smoke radiation. Finally, jump conditions are derived to account for the rapid changes in physical quantities at the fire periphery. They effect model problem closure, and decouple the turning-region analysis from that of other component flows. An iterative

finite-difference scheme, documented in the Appendix, is employed to solve the resultant boundary value problem.

We study the large urban fire environment in two ways--by varying parameters and by simulating three model cities. In the parametric analysis, excursions are made about a baseline in which the fire radius is taken to be 10 km and the characteristic heat release rate is consistent with that of the 1943 Hamburg firestorm [DCPA, 1973]. Predictions of hurricane-force winds are typical in the parameter excursions as well as the model city simulations, which consider fires of radius 12 km with spatially varying heating rates on the order of those in the parametric analysis. That is believed to be about the size of the fire that would result from a near-surface nuclear burst of about 1 Mt [Johnson and Larson, 1982].

Section II presents the results of the parametric analysis. As expected, temperatures and fire-wind velocities increase with an increase in either fire size or burning rate, though the fire-wind variations are not as rapid as the linear scaling law of Part I suggests. Also as expected, temperatures and winds increase with a decrease in radiation intensity; winds also increase with a decrease in the magnitude of the eddy coefficient for turbulent momentum transfer. The temperature field is relatively insensitive to changes in that coefficient, however, and both winds and temperature are relatively insensitive to changes in the corresponding coefficient for turbulent heat transfer.

The basic flow pattern also seems to be relatively insensitive to variations in the specific dependence of the heat release rate on spatial position, though such variations modify velocities slightly and may significantly change the temperature field. That behavior is found when model predictions for a uniformly heated, circular fire are compared with those for an annular fire. The comparison indicates how partial blast extinguishment would modify the hydrothermodynamic environment generated by a nuclear-weapon-ignited fire. It also provides a first look at the catastrophic effect of multiple weapon bursts.

Section III describes the model city simulations. Three model cities are defined: one that is lightly built-up, intended to represent new, sprawling cities; one that is heavily built-up, intended to represent old, congested cities; and one of intermediate building density. For each city, spatially dependent fuel loadings and peak-period burning rates for a baseline fire are estimated, and the resulting temperatures, pressures, and fire winds predicted. Those calculations are repeated for a scenario in which the fire is ignited by a nuclear burst and the city partially destroyed by the attendant blast.

Somewhat surprisingly, despite a significant difference in model-city temperature predictions for the "blast" and "no blast" simulations, the corresponding difference in induced fire winds is fairly small. Such behavior suggests that the winds and wind damage resulting from nuclear-weapon-ignited fires may be relatively independent of the degree of blast extinguishment--unless, of course, extinguishment is nearly complete.

As expected, however, temperatures and fire-wind velocities all increase with building density. For a given fire size, the large-fire threat facing civil defense workers will thus be more severe in the tall, heavily loaded cities than in the short, lightly loaded cities. In general, however, the shorter cities sprawl out over greater land areas than do taller ones of comparable population, and are thus capable of supporting larger fires. The large-fire threat for any given population size may thus be greatest in some of the shorter cities, especially if the fires result from multiple nuclear bursts. Comparisons between specific cities must be made individually.

Finally, Sec. IV presents a sample application of the quasi-steady model of Part I to obtain time-dependent predictions. The sample case considers multiple-fuel-bed Flambeau fires, the largest area fires for which a reasonable body of technical data exists [Countryman, 1969; Palmer, 1981].

II. PARAMETRIC ANALYSIS OF LARGE-FIRE ENVIRONMENT

Using the turning-region model of Part I, this section explores the dependence of the large-fire environment on fire size (height and radius), burning rate (spatial average and form), degree of turbulent mixing, and degree of hot-gas radiation.

Briefly, with r , y , u , v , ρ , T , and P denoting dimensionless radial and vertical position, radial and vertical velocity, density, temperature, and perturbation pressure, respectively, the turning-region equations are as follows:

$$\frac{\partial}{\partial r} (r\rho u) + \frac{\partial}{\partial y} (r\rho v) = 0 , \quad (1a)$$

$$\rho \left(u \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial P}{\partial r} + M_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) - \frac{u}{r^2} \right) , \quad (1b)$$

$$\frac{\partial P}{\partial y} + A\rho = 0 , \quad (1c)$$

$$\rho \left(u \frac{\partial T}{\partial r} + v \frac{\partial T}{\partial y} \right) = q(r, y) - \sigma(T^4 - 1) + K_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right) , \quad (1d)$$

$$\rho T = 1 , \quad (1e)$$

where the dimensionless parameters are

$$A = \frac{gH}{U^2} ,$$

$$U = \frac{\gamma - 1}{\gamma} \left(\frac{R}{H} \right) \left(\frac{QH}{P_a} \right) ,$$

$$\sigma = 4\pi\hat{\sigma}T_a^4 \left(\frac{k^*H}{QH} \right) , \quad (2)$$

and

$$M_1 = \frac{\mathcal{E}_1 / \rho_a}{UR},$$

$$K_1 = \frac{k_1 / c_p \rho_a}{UR}. \quad (3)$$

Here, R and H denote fire radius and maximum flame height; Q the scale and $q(r, y)$ the spatial distribution for the rate of volumetric heat addition; and P_a , ρ_a , and T_a ground-level atmospheric pressure, density, and temperature in the far field, respectively. Further, $\hat{\sigma}$ is Stefan's constant, k^* is the reciprocal of the graybody radiation mean free path (assumed constant), and \mathcal{E}_1 and k_1 are dimensional eddy coefficients for turbulent momentum and heat transfer.[†]

We consider the dependence of model predictions on the size parameters R and H , the burning rate parameters QH^{++} and $q(r, y)$, the radiation mean free path k^{*-1} , and the dimensionless eddy coefficients M_1 and K_1 . The terms \mathcal{E}_1 / ρ_a and $k_1 / c_p \rho_a$ remain constant, except when variations with M_1 and K_1 are specifically studied.

BASELINE ANALYSIS

As a baseline case, we consider an axisymmetric fire with the following parameters:

$$R = 10 \quad \text{km}, \quad (4a)$$

$$H = 100 \quad \text{m}, \quad (4b)$$

$$QH = 5.7 \times 10^4 \quad \text{cal/m}^2\text{-sec}, \quad (4c)$$

[†]As in Part I, g is the acceleration due to gravity, γ the specific heat ratio, and U the radial velocity scale. The vertical velocity is scaled with $(H/R)U$, temperature and density with T_a and ρ_a , and perturbation pressure with δP_a , where $\delta = U^2 / (P_a / \rho_a)$.

⁺⁺ QH is used as a parameter instead of Q because areal heat release rates are encountered much more frequently than volumetric rates in the large-fire literature.

$$q(r, y) = \begin{cases} 1.6 & \text{for } 0 \leq y \leq 0.25 \\ 1.6 \left(\frac{4}{3} (1 - y) \right) & \text{for } 0.25 \leq y \leq 1.0 , \\ 0 & \text{for } y \geq 1.0 \end{cases} \quad (4d)$$

$$M_1 = K_1 = 0.2 , \quad (4e)$$

$$k^{*-1} = 20 \quad m . \quad (4f)$$

The heat release rate in this case is the same as that in our simulation in Part I of the 1943 Hamburg firestorm, and is characteristic of the rates estimated in Sec. III for a variety of U.S. cities. The parameter QH is the nominal specific scale rate suggested by DCPA [1973]. The form of $q(r, y)$ represents maximum heating in and around the fuel zone and a decrease in heating with increased altitude. All other parameter choices used in Eqs. (4) are of the same order as those used in the model city analysis.

From Eqs. (2) and (4), the radial velocity scale for the baseline case is

$$U = 67.2 \quad m/sec , \quad (5)$$

and

$$A = 0.217 ,$$

$$\sigma = 0.110 . \quad (6)$$

The temperatures, pressures, and velocities predicted for this case are summarized in the vector, contour, and profile plots of Figs. 1 through 5. The flow field is illustrated in Fig. 1. Temperature and pressure contours are plotted in Figs. 2 and 3, respectively. The temperature attains a maximum in the fire center at the top of the maximum heating zone ($y = 0.25$). It then decreases rapidly with increased altitude, the flow becoming weakly buoyant above three

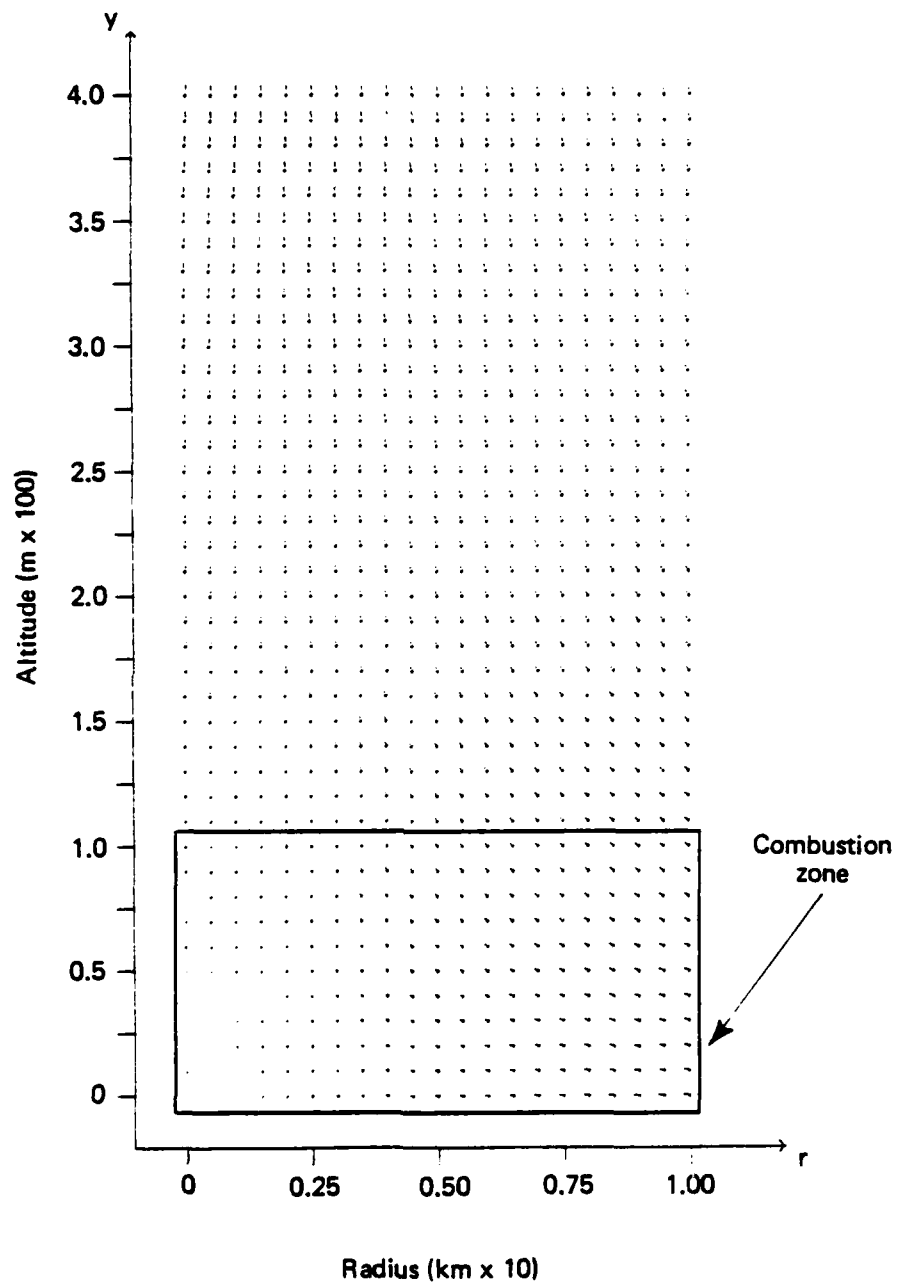


Fig. 1--Velocity field for baseline fire

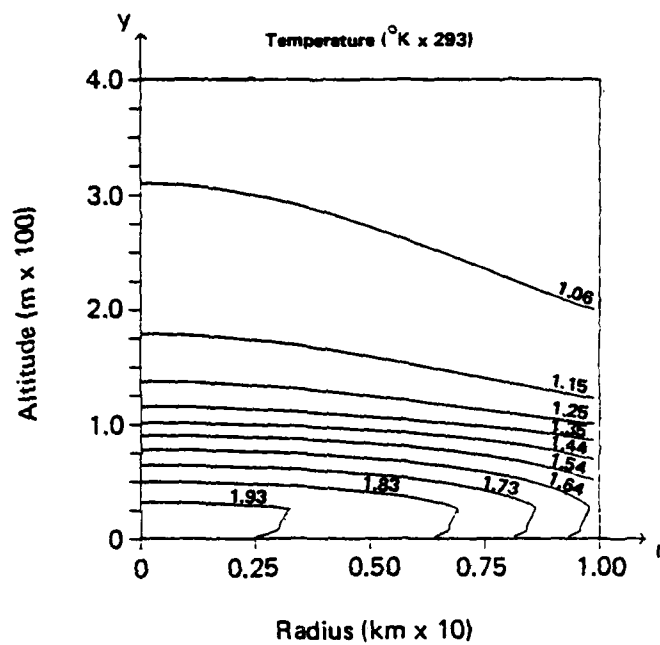
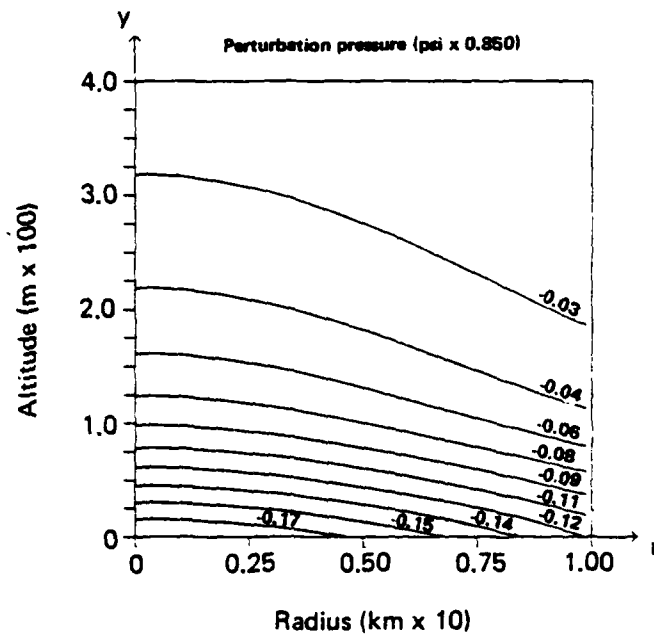


Fig. 2--Temperature contours for baseline fire



Note: Perturbation pressure is $\delta P_g (P + \Delta y)$; see footnote † on p. 8.

Fig. 3--Pressure contours for baseline fire

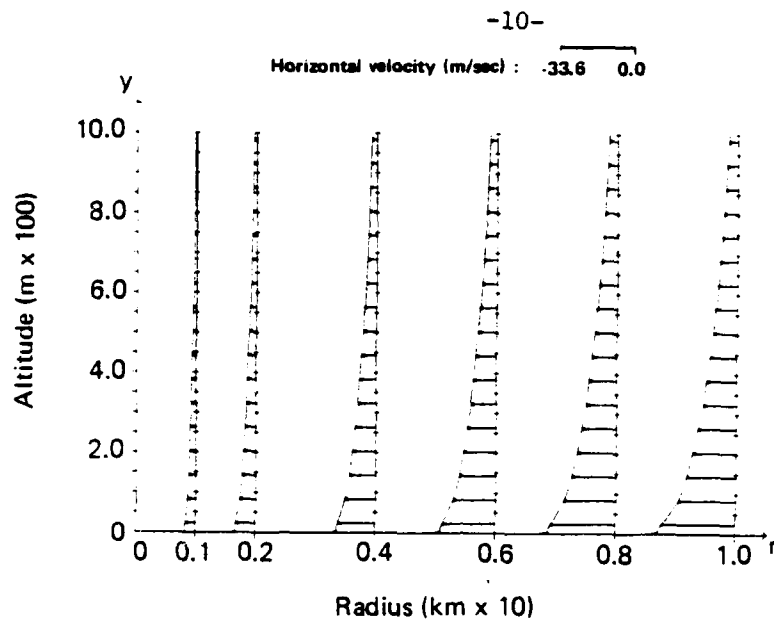


Fig. 4--Radial velocity profiles for baseline fire

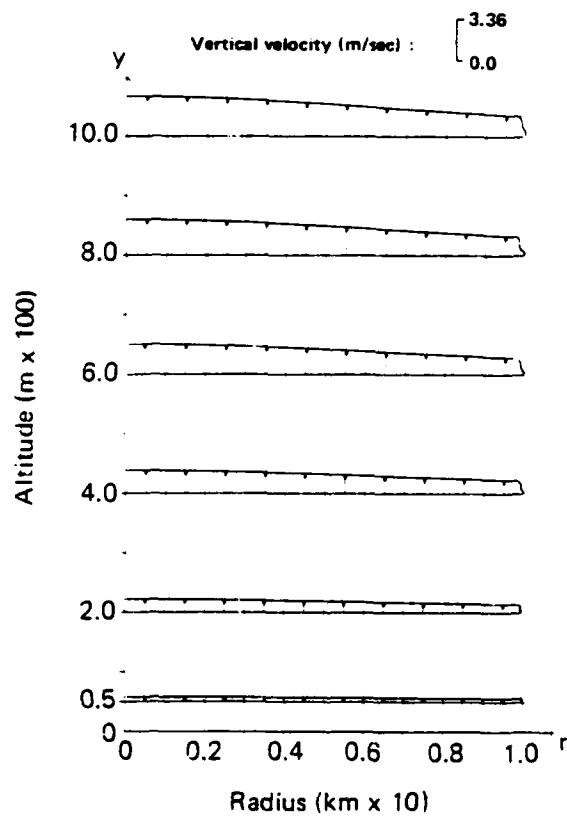


Fig. 5--Vertical velocity profiles for baseline fire

flame heights. As expected, the pressure drop is maximum at ground level. Profiles of the horizontal inflow induced by the pressure drop are presented in Fig. 4, and those of the resulting upflow in Fig. 5. The maximum inflow occurs on the ground at the fire periphery. The upflow profiles are nearly "top-hat."

In most parameter excursions, the hydrothermodynamic predictions are qualitatively the same as those for the baseline case. The results are summarized below.

DEPENDENCE ON FIRE SIZE AND BURNING RATE SCALE

We consider first the dependence of the large-fire environment on R , H , and QH --the parameters that collectively describe the fire. For nuclear-weapon-ignited fires, the effective value of R will depend on the number and yields of bursts, ambient atmospheric conditions, various characteristics of the preblast urban area (e.g., flammability of exposed combustibles, susceptibility of structures to secondary fires), and a variety of lesser factors [Johnson and Larson, 1982]]. Parameters QH and H will depend on the type and distribution of combustibles in the postblast environment, as detailed in Sec. III.

Tables 1 through 3 summarize the variations that we consider in fire size and burning rate, and the corresponding changes in model parameters that follow from Eqs. (2) and (3). In most excursions, the variations are of the type in Table 2, where the parameter under study is simply doubled or halved. The additional variations in Tables 1 and 3 are considered in order to refine the excursions that we believe to be of greatest intrinsic interest--i.e., those defining the dependence of fire winds and temperatures on fire radius (weapon coverage) and intensity (concentration of combustibles).

Figures 6 through 11 summarize the results of the fire size and burning rate excursions. The dependence of fire winds and temperatures on fire size and intensity is plotted in Figs. 6 through 8. As expected, the maximum induced velocity u_{\max} and the maximum temperature T_{\max} both increase with either radius or intensity. The increases are nearly linear for relatively small radii and heating rates,

Table 1

PARAMETER DEPENDENCE ON FIRE RADIUS

R (km)	U (m/sec)	A	σ	M_1, K_1
2.5	16.8	3.4720	0.110	3.200
5.0	33.6	0.8680	0.110	0.800
10.0	67.2	0.2170	0.110	0.200
15.0	100.8	0.0964	0.110	0.089
20.0	134.4	0.0534	0.110	0.050

Table 2

PARAMETER DEPENDENCE ON FIRE HEIGHT

H (m)	U (m/sec)	A	σ	M_1, K_1
50	134.4	0.0272	0.055	0.4
100	67.2	0.2170	0.110	0.2
200	33.6	1.7360	0.220	0.1

Table 3

PARAMETER DEPENDENCE ON BURNING RATE SCALE

QH (kcal/m ² -sec)	U (m/sec)	A	σ	M_1, K_1
14.35	16.8	3.4720	0.4400	0.80
28.70	33.6	0.8680	0.2200	0.40
57.40	67.2	0.2170	0.1100	0.20
86.10	100.8	0.0964	0.0825	0.15
114.80	134.4	0.0534	0.0550	0.10

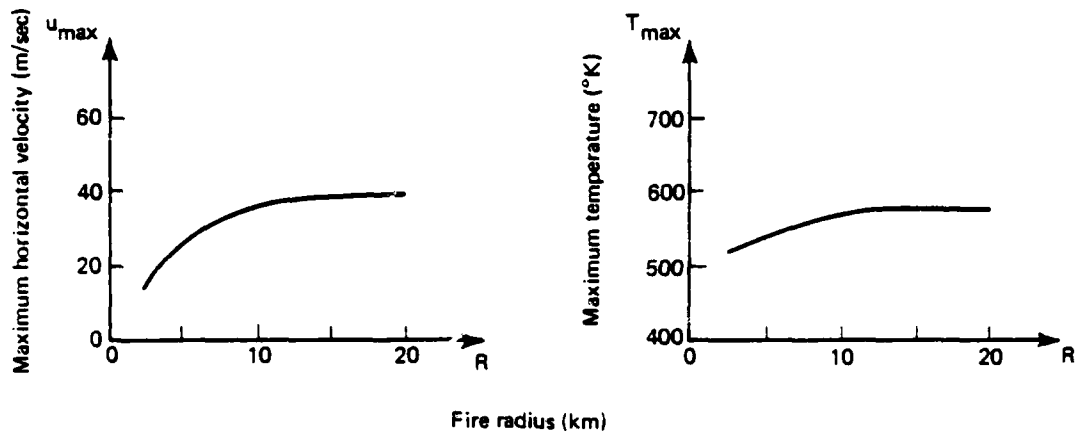


Fig. 6--Dependence of maximum radial velocity and temperature on fire radius

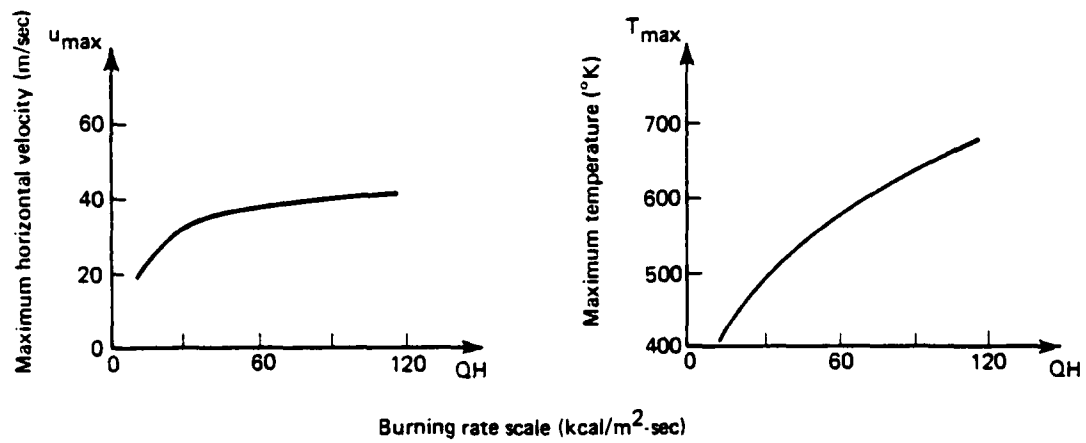


Fig. 7--Dependence of maximum radial velocity and temperature on burning rate scale

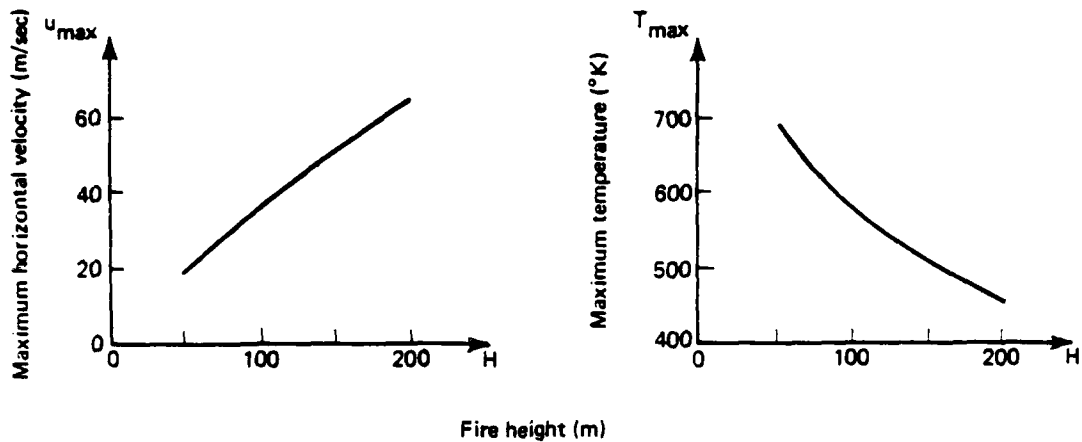


Fig. 8--Dependence of maximum radial velocity and temperature on fire height

but tail off markedly for fires of much greater size and intensity. In fact, u_{max} and T_{max} appear to asymptote toward finite values as R or $QH \rightarrow \infty$. Surprisingly, the apparent asymptotic values of u_{max} as either R or $QH \rightarrow \infty$ are almost identical. T_{max} , however, exhibits a stronger dependence on QH than on R .

Figure 8 describes the variation of u_{max} and T_{max} with fire height. As H increases, u_{max} increases but T_{max} decreases. Such behavior is presumably explained as follows. With QH fixed, Q decreases when H increases. Temperature decreases correspondingly, because of the shorter characteristic residence times of fluid particles in the heating zone. Lower temperatures might be expected to decrease velocities as well. However, a smaller fraction of the constant total heat release QH is radiated away at lower temperatures, so higher kinetic energies can be supported.

The results in Fig. 8 must be interpreted with some care. Whenever H is varied, QH may be varied as well. For example, when buildings have the same construction and contents, both H and QH should

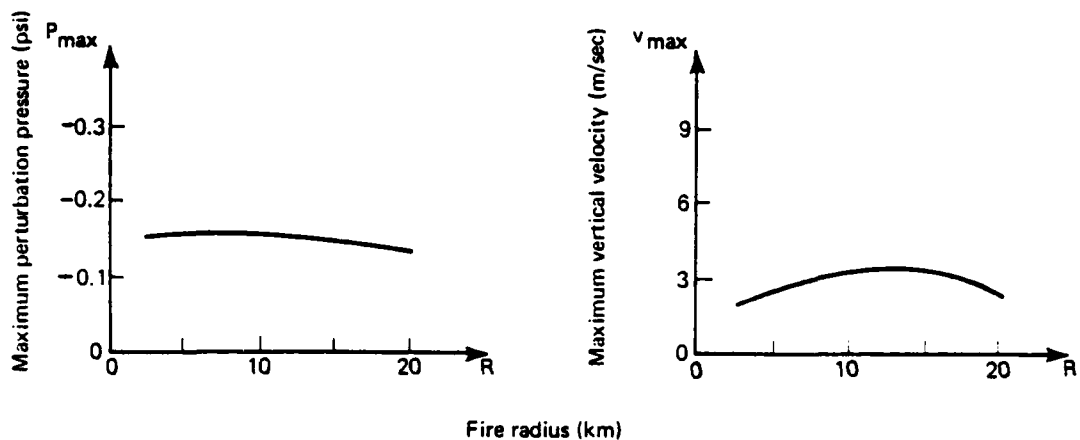


Fig. 9--Dependence of maximum perturbation pressure and vertical velocity on fire radius

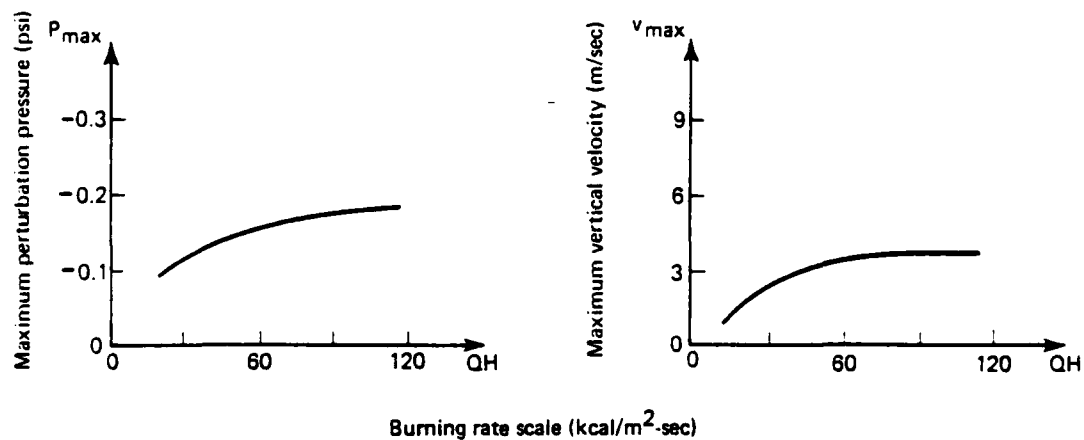


Fig. 10--Dependence of maximum perturbation pressure and vertical velocity on burning rate scale

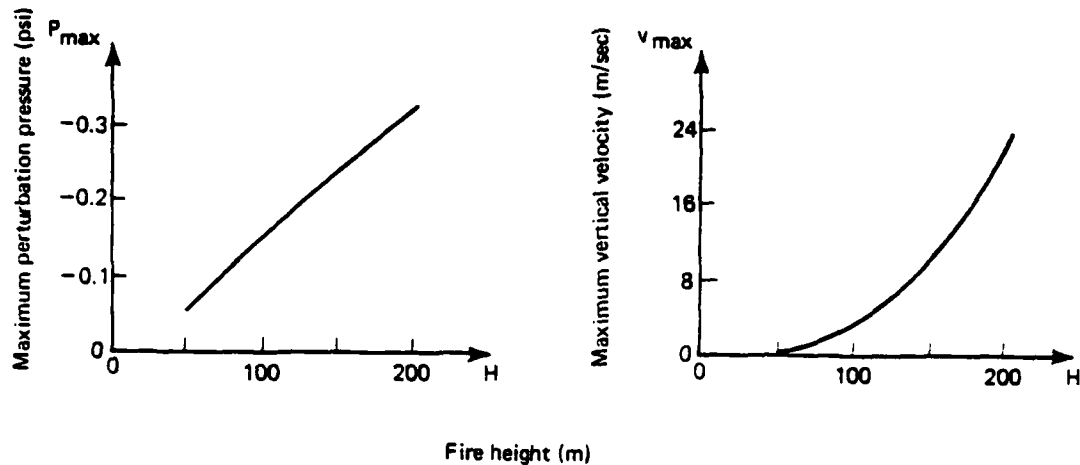


Fig. 11--Dependence of maximum perturbation pressure and vertical velocity on fire height

increase with the number of stories. In such cases, the results in Fig. 7 may be more applicable.

Figures 9 through 11 plot the dependence of maximum pressure drop P_{max} and vertical velocity v_{max} on R , QH , and H . As expected, vertical velocities generally increase with radial velocities. Greater pressure gradients foster greater radial velocities, and are less strongly correlated with temperature variations than Eq. (1c) suggests.

DEPENDENCE ON BURNING RATE SPATIAL DISTRIBUTION

We now briefly explore the effects of different spatial dependences of the heat release rate $q(r, y)$. We consider several sinusoidal and annular variations in radial dependence, but just one in vertical dependence. Further variations are considered in the model city analysis in Sec. III.

Table 4 summarizes the variations in $q(r, y)$ and the resulting hydrothermodynamic changes. As expected, a relatively high-frequency

Table 4

VELOCITY, TEMPERATURE, AND PERTURBATION PRESSURE MAXIMA
FOR VARIOUS BURNING RATES

Type of Fire	$\left(\frac{q(r, y)}{\{q(r, y)\}_{\text{baseline}}} \right)$	u_{max} (m/sec)	T_{max} (°K)	P_{max} (psi)	v_{max} (m/sec)
Baseline	1.0	37.2	570	0.156	3.26
Sinusoidal					
Low-frequency	$1.0 - \cos 4\pi r$	38.1	588	0.160	3.50
High-frequency	$1.0 - \cos 20\pi r$	37.2	573	0.157	3.28
Annular	$\begin{cases} 0.0 & \text{for } 0 \leq r < 0.5 \\ 1.0 & \text{for } 0.5 \leq r \leq 1 \end{cases}$	33.9	515	0.119	2.46

radial variation on the baseline heat-release distribution has little effect. Surprisingly, however, a fairly low-frequency radial variation also produces trivial changes in velocity, temperature, and perturbation pressure. Those results suggest that the large-fire environment may be more sensitive to the basic scale for heat release than to the specific spatial distribution of the heat release rate (see Fig. 7).

That conclusion is further supported by a comparison of the results in Table 4 for the annular fire with those for the circular baseline fire. The ground area covered by the annular fire--and hence its total heat release--is 25 percent less than that of the baseline fire. The corresponding drop in maximum temperature difference from ambient (i.e., in $T_{\text{max}} - T_a$) is just slightly less--20 percent. The drop in u_{max} is significantly less--only 9 percent. Such behavior suggests that the maximum winds and temperatures generated by nuclear-weapon-ignited urban fires may be relatively insensitive to changes in the geometry and loading of the blast-damaged region, provided of course that the blast does not nearly extinguish the fire.

Figures 12 and 13 compare the temperature and flow fields of the baseline and annular fires. Since the fire is located only in the annulus, the highest temperatures occur near the inner edge of the fire annulus ($r = 0.5$), rather than on the symmetry axis. The resulting

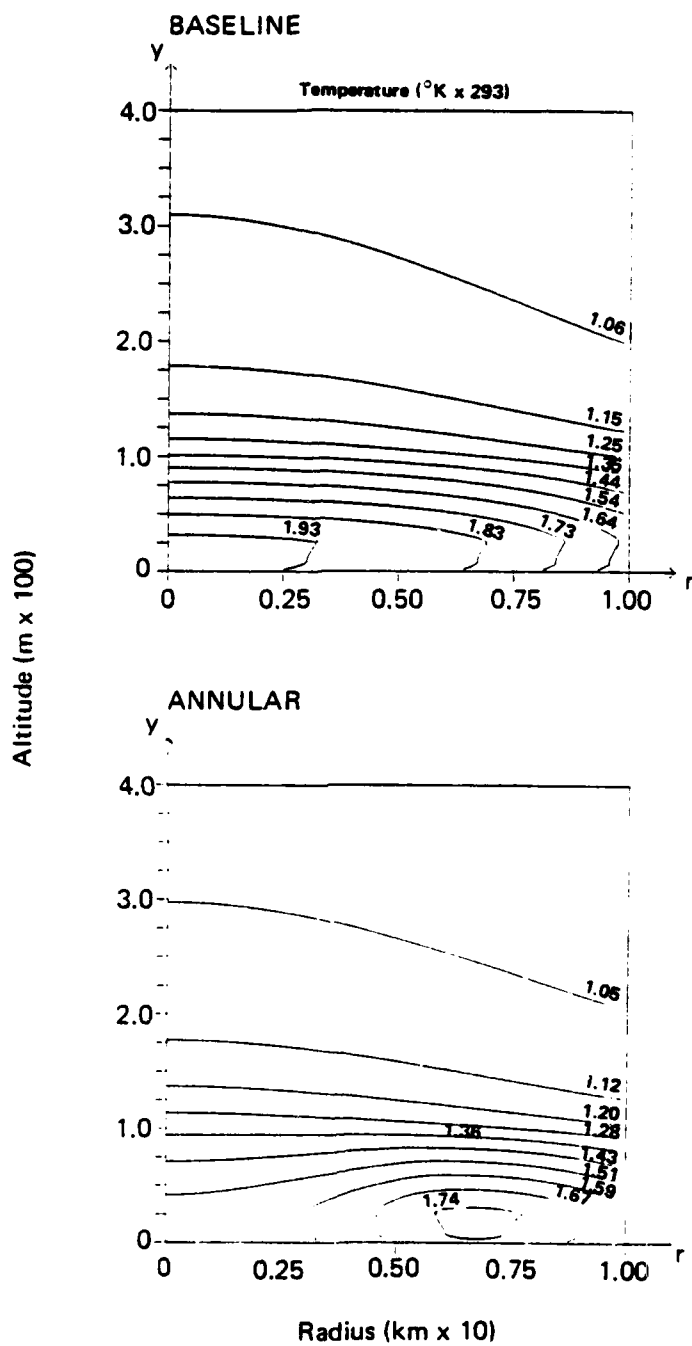


Fig. 12--Temperature contours of baseline and annular fires

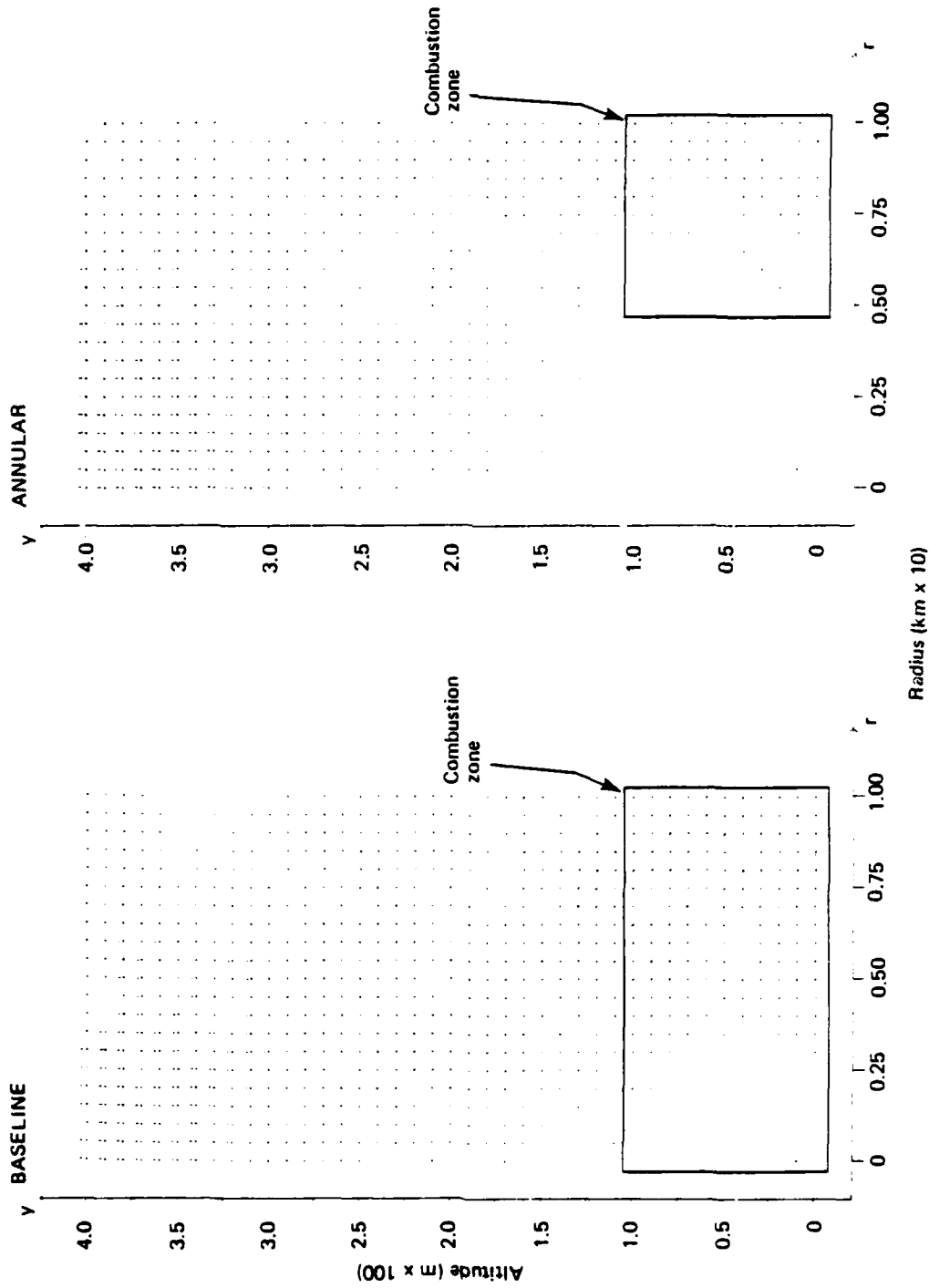


Fig. 13--Flow fields of baseline and annular fires

temperature field is thus qualitatively different from that of the baseline fire. Further, as Fig. 13 shows, winds in the annular fire do not blow toward the fire from both edges of the annulus. Rather, they blow inward (toward the symmetry axis) and upward at all points, as do those in the baseline fire. By means of heat convection and branding, annular fires might therefore be expected to spread inward.

Similarly, a cluster of separated large fires, such as could result from multiple nuclear bursts over a large city, might coalesce and engulf much of the intervening region. The patterns of airflow and fire spread envisioned for such situations are sketched in Figs. 14 and 15. The cluster of fires represented in Fig. 14 nearly forms an annulus, as indicated by the dashed circles. The fire-wind flow

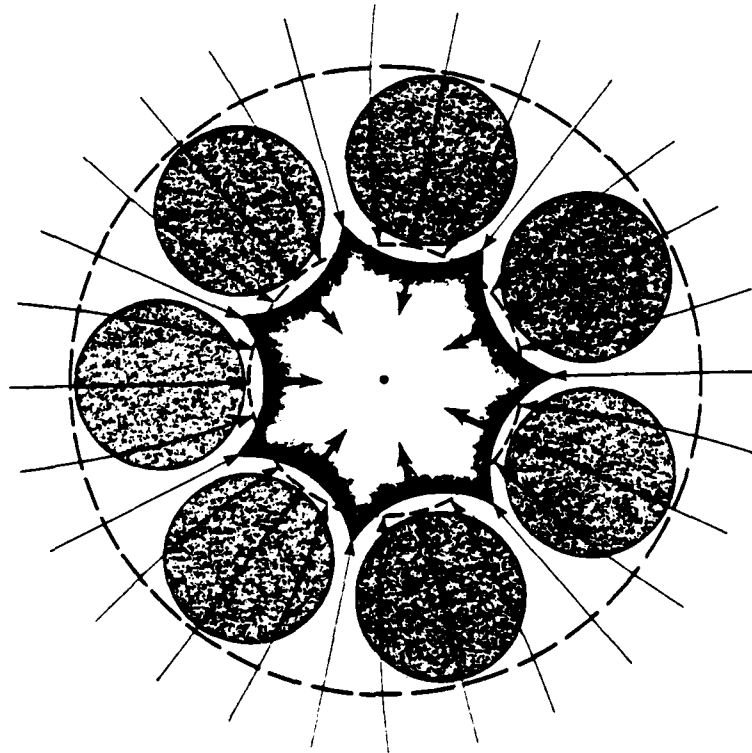


Fig. 14--Radial airflow and fire spread patterns suggested for annular cluster of large area fires

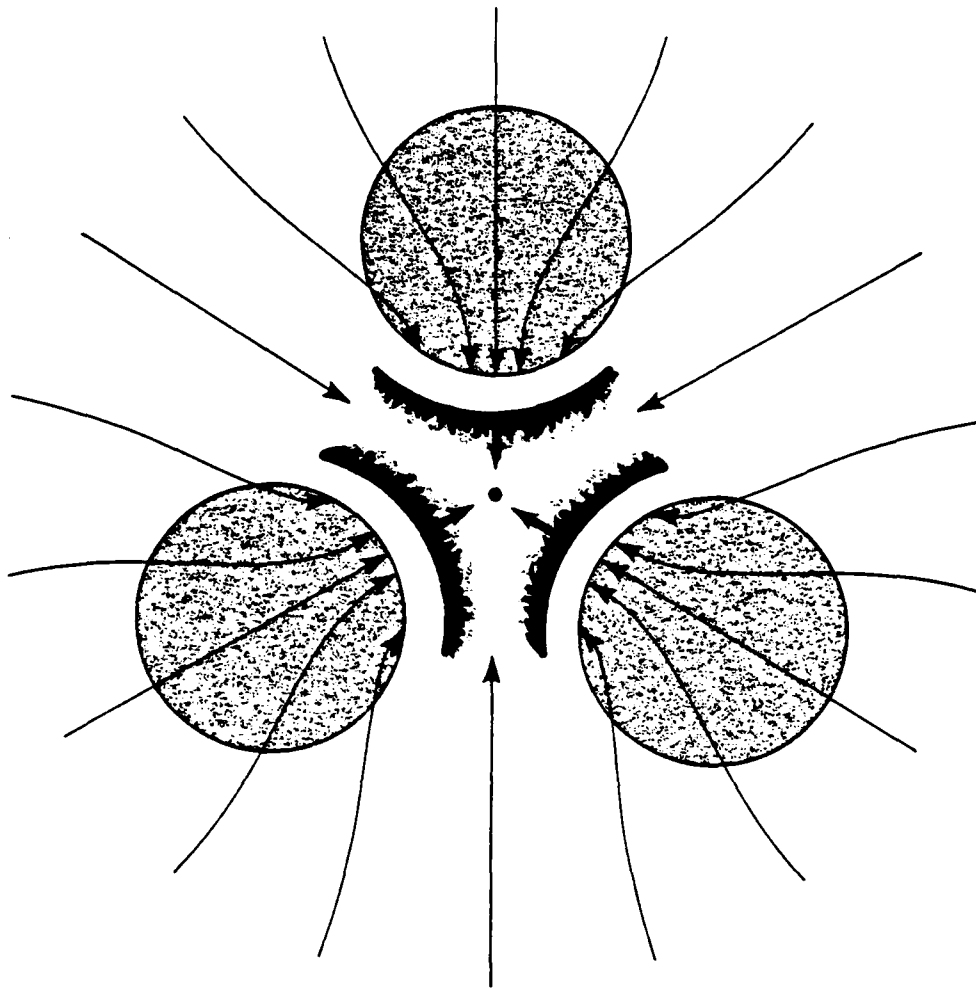


Fig. 15--Radial airflow and fire spread patterns suggested for cluster of three large area fires

should thus be nearly axisymmetric and of the type illustrated in Fig. 13. Correspondingly, the fire should spread inward, and may ultimately cover much of the area inside the inner dashed curve. As shown in Fig. 15, the flow and spread patterns for asymmetric clusters should be less axisymmetric, but still basically inward. Such hypotheses could presumably be verified by extensive, three-dimensional numerical computations.

We now consider a variation of heat release rate with altitude. Specifically, we compare the results for the baseline [$q(r, y)$ defined by Eq. (4)] with those for the more uniform case where q is independent of y --and hence constant. That comparison, summarized in Table 5, reflects the results illustrated in Figs. 8 and 11. For less concentrated heat releases, temperatures are lower, but pressure drops and velocities are greater.

Table 5
VELOCITY, TEMPERATURE, AND PERTURBATION PRESSURE MAXIMA
FOR BASELINE AND UNIFORM FIRES

Type of Fire	$q(r, y)$	u_{\max} (m/sec)	T_{\max} (°K)	P_{\max} (psi)	v_{\max} (m/sec)
Baseline	$\begin{cases} 1.6 & \text{for } 0 \leq y \leq 0.25 \\ 1.6 \left(\frac{4}{3}\right) (1 - y) & \text{for } 0.25 \leq y \leq 1 \\ 0 & \text{for } y \geq 1 \end{cases}$	37.2	570	0.156	3.26
Uniform	1.0	50.9	497	0.231	7.19

DEPENDENCE ON TURBULENCE AND RADIATION

Finally, we consider the variation of the large-fire environment with the eddy coefficients M_1 , K_1 and the graybody radiation parameter k^* . The results are summarized in Figs. 16 through 23.

The dependence of fire winds and temperatures on eddy coefficients is demonstrated by Figs. 16, 17, and 18. As expected, the maximum radial velocity decreases with an increase in the eddy coefficient for momentum transfer (Fig. 16). Correspondingly, the maximum temperature increases. An increase in the eddy coefficient for heat transfer might also decrease temperatures, and hence increase velocities. In Fig. 17, such variations are shown to occur, but so weakly that both T_{\max} and u_{\max} must be considered almost independent of K_1 . When M_1 and K_1 are varied together, as in Fig. 18, the results are thus similar to those with only M_1 varied (cf. Fig. 16).

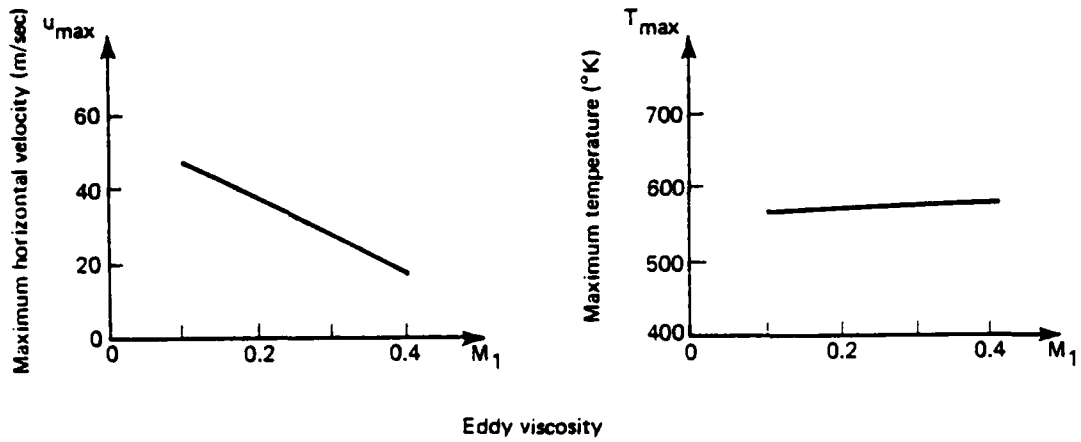


Fig. 16--Dependence of maximum radial velocity and temperature on eddy coefficient for momentum transfer

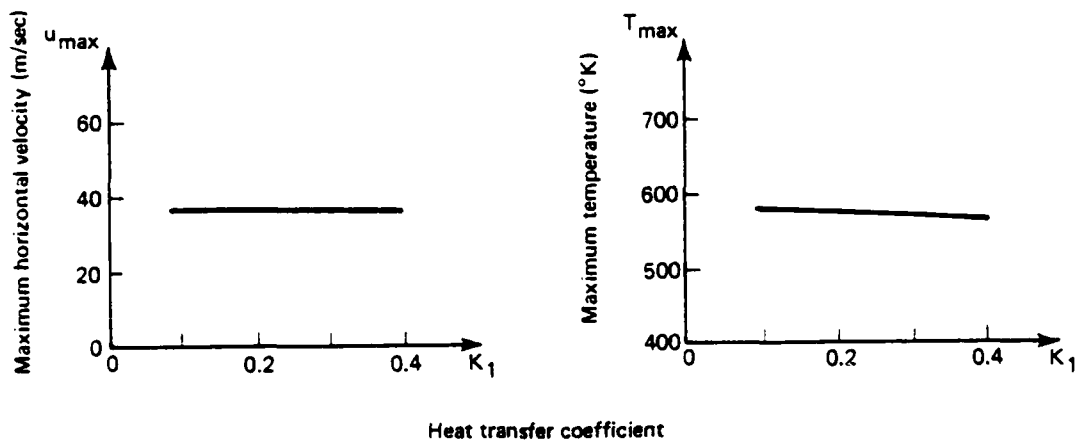


Fig. 17--Dependence of maximum radial velocity and temperature on eddy coefficient for heat transfer

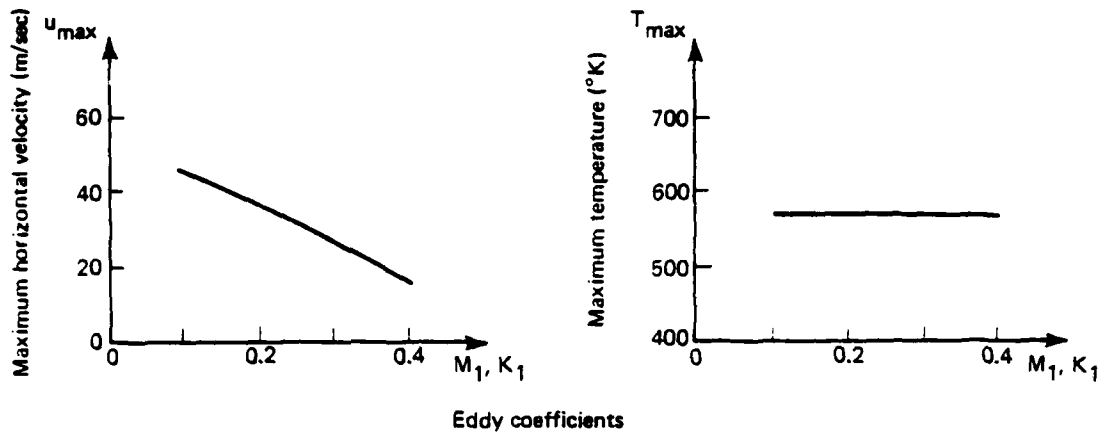


Fig. 18--Dependence of maximum radial velocity and temperature on eddy coefficients

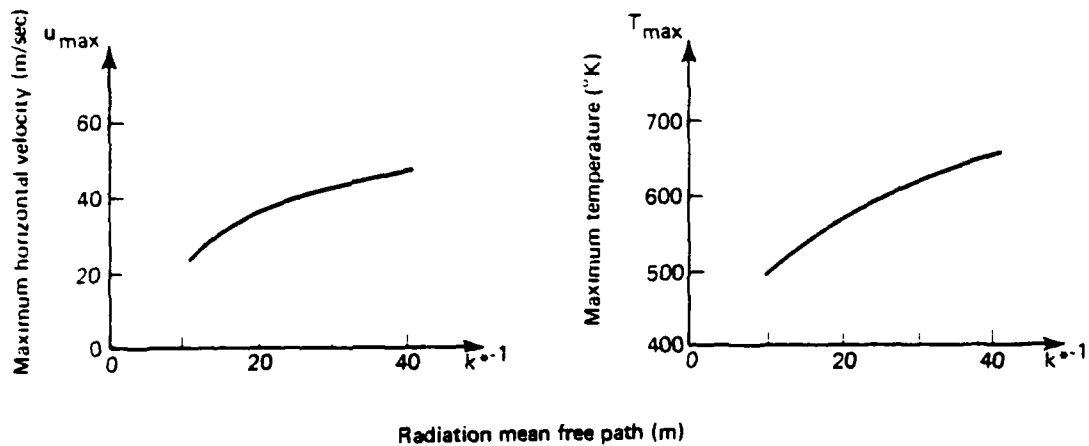


Fig. 19--Dependence of maximum radial velocity and temperature on radiation mean free path

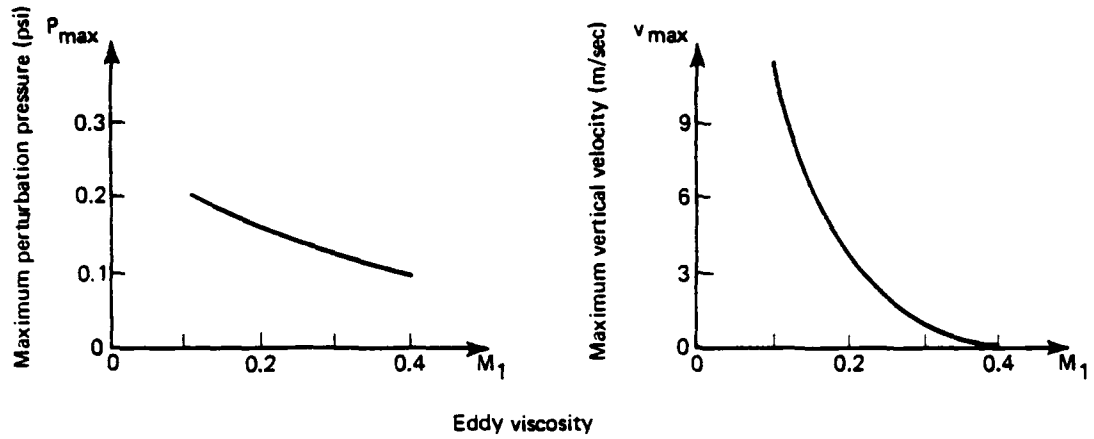


Fig. 20--Dependence of maximum perturbation pressure and vertical velocity on eddy coefficient for momentum transfer

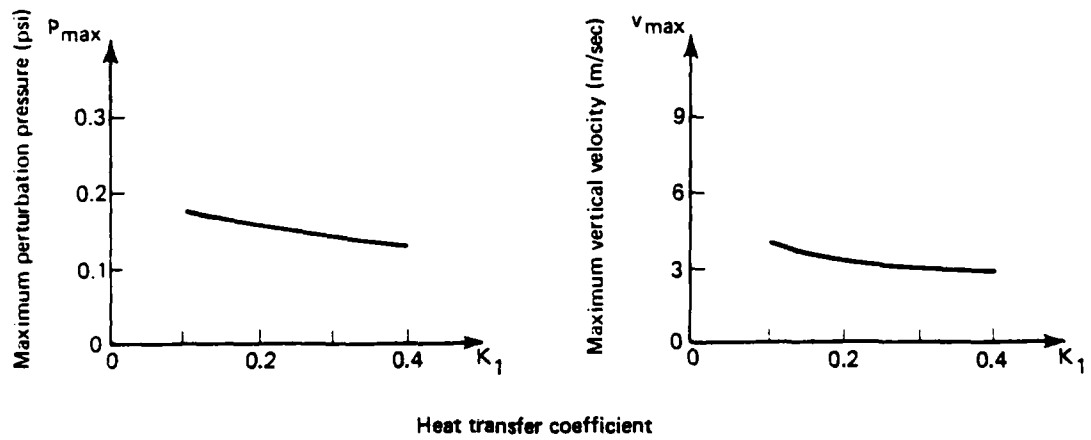


Fig. 21--Dependence of maximum perturbation pressure and vertical velocity on eddy coefficient for heat transfer

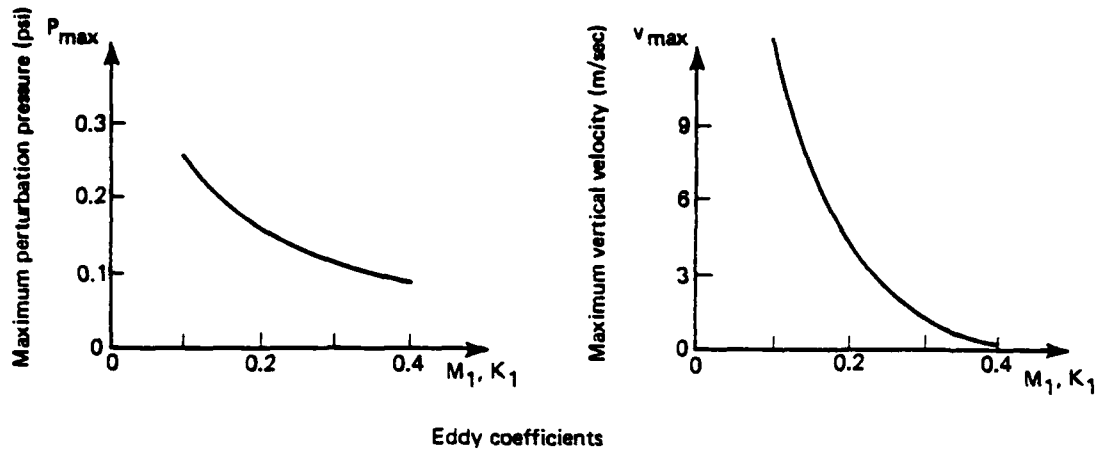


Fig. 22--Dependence of maximum perturbation pressure and vertical velocity on eddy coefficients

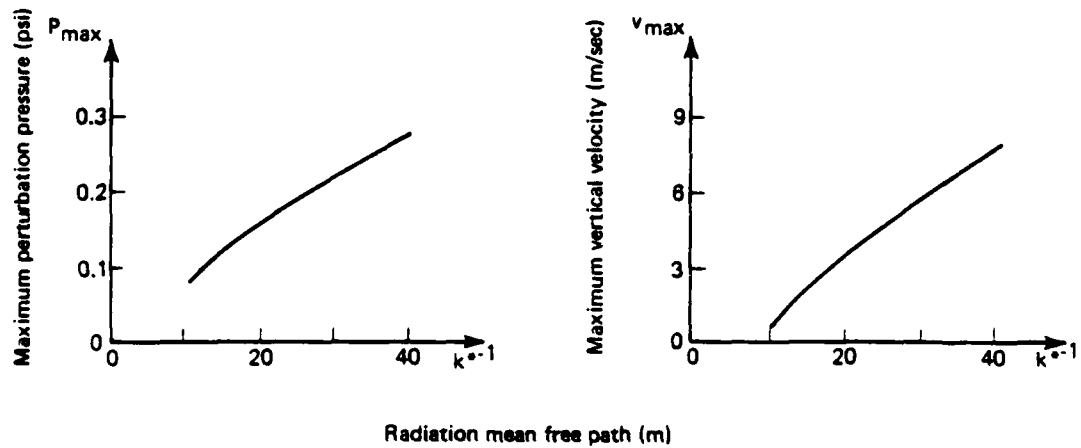


Fig. 23--Dependence of maximum perturbation pressure and vertical velocity on radiation mean free path

Figure 19 indicates the dependence of fire winds and temperatures on the radiation parameter k^* . Both winds and temperatures increase with k^{*-1} --as expected, since the effective scale for radiative energy loss σ is proportional to k^* [see Eqs. (1) and (2)].

The dependence of pressure drops and vertical velocities on M_1 , K_1 , and k^* is shown by Figs. 20 through 23. As in previous comparisons (Figs. 6 through 11 and 16 through 19), variations in those parameters are strongly correlated with variations in radial velocity.

III. MODEL CITY ANALYSIS

Using the turning-region analysis of Part I, we obtain predictions of the large-fire environment for three model U.S. cities. City W is lightly built-up, and intended to represent new, sprawling cities. City E is heavily built-up, and intended to represent old, congested cities. City M is of intermediate building density. For each city, two cases are considered: a baseline fire and one modified by blast. In all cases, however, the fire radius is taken to be 12 km--believed to be about the size of the fire that would result from a 1 Mt near-surface nuclear burst [Johnson and Larson, 1982].

DEFINITION

Few metropolitan areas are axisymmetric. Nevertheless, most cities have a main business district with high-rise office and apartment buildings, surrounded by lower density tracts. Our model cities reflect that situation. Each has three regions: a tall central city; a residential/industrial belt of intermediate height around the central city; and a low, primarily residential outer belt. We refer to those regions as the central city, inner belt, and outer belt, respectively.

Table 6 summarizes the geometry of the model cities, including both the horizontal extent of each city region, the corresponding vertical extent N_s (average number of stories), and the building density f_{Bu} . We assume that the top and bottom stories are each 4 m high and all other stories are 3 m high.[†] The values for building density f_{Bu} in each model city region are comparable to those in the DCPA manual, and thus considered representative of U.S. cities [DCPA, 1973]. The values are all less than 0.45, which approximates the densely packed Hamburg districts devastated in the firestorm of 1943 (see Part I).

[†]The average heights of the outer-belt buildings in cities W and E are taken to be 6 and 10 m, respectively.

Table 6
SIZE AND DENSITY OF MODEL CITY REGIONS

Region	City		
	W	M	E
<i>Radial Dimension (km)</i>			
Central city	0-1	0-1	0-2
Inner belt	1-3	1-4	2-6
Outer belt ^a	3-12	4-12	6-12
<i>Average Number of Stories, N_s</i>			
Central city	8	12	16
Inner belt	3	4	6
Outer belt	1.5	2	2.5
<i>Building Density, f_{Bu}^b</i>			
Central city	0.30	0.35	0.40
Inner belt	0.25	0.30	0.35
Outer belt	0.15	0.20	0.25

^aRadius of outer belt may extend beyond 12 km, but the fire does not.

^bCalculated as the ratio of land area covered by buildings to total land area.

The corresponding geometry of the baseline model-city fire simulations is summarized in Figs. 24 through 26. In each figure, the shaded area represents the fuel zone (defined by Table 6) and the hatched area represents the remainder of the combustion zone. The total height of the combustion zone in the outer belt is assumed to be five times the fuel zone height.[†] Since turbulence will break the flame envelope and tend to keep flame heights uniform [Thomas, 1963], the ratio of combustion zone height to fuel zone height in the central city is taken as only half as much; the combustion zone height in the inner belt is assumed to be the average of the other two.

[†]As noted in Part I, a combustion-zone-height to fuel-zone-height ratio of about five was observed for the largest Flambeau fires and the 1943 Hamburg firestorm.

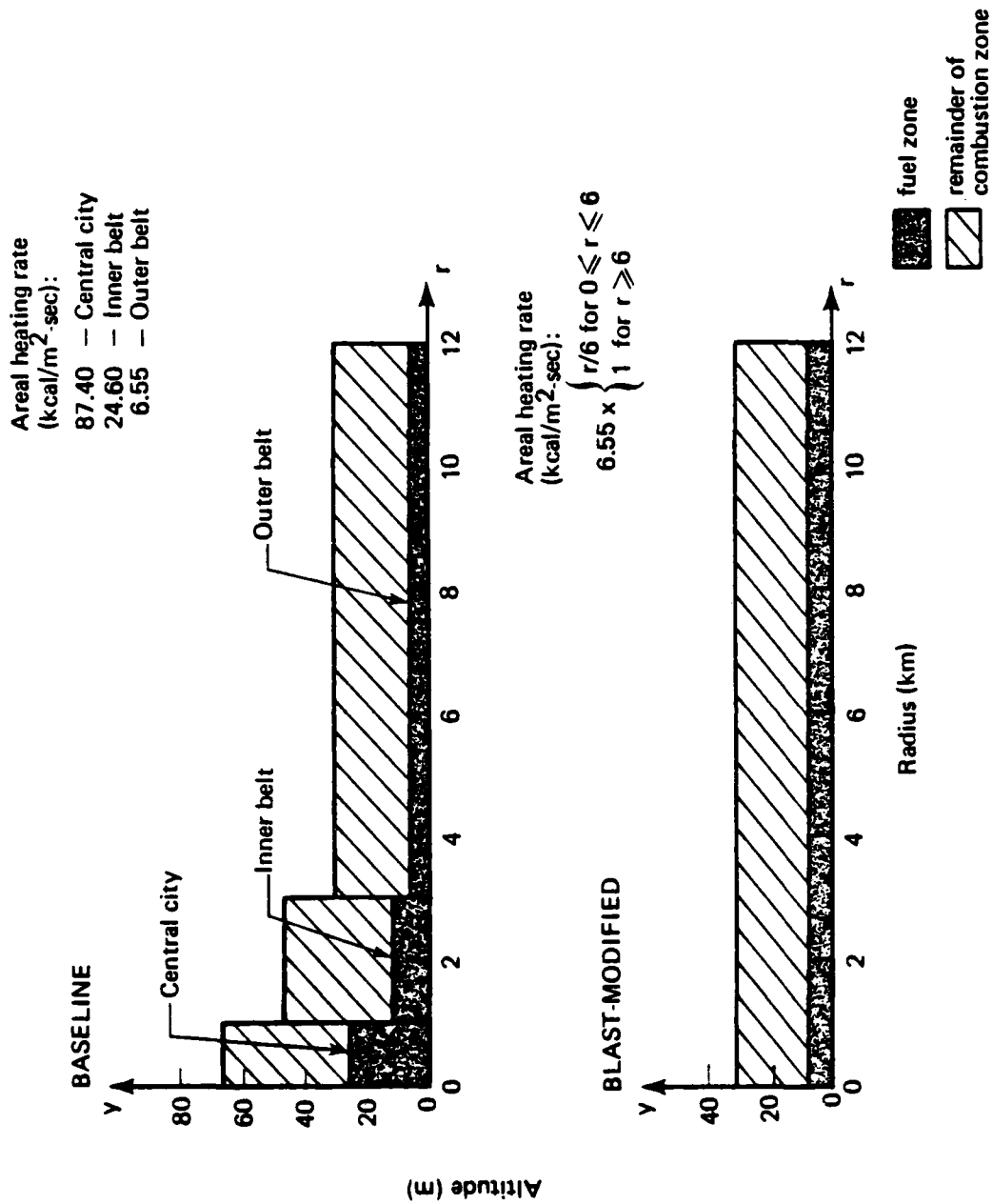


Fig. 24--Fire schematic for baseline and blast-modified city W

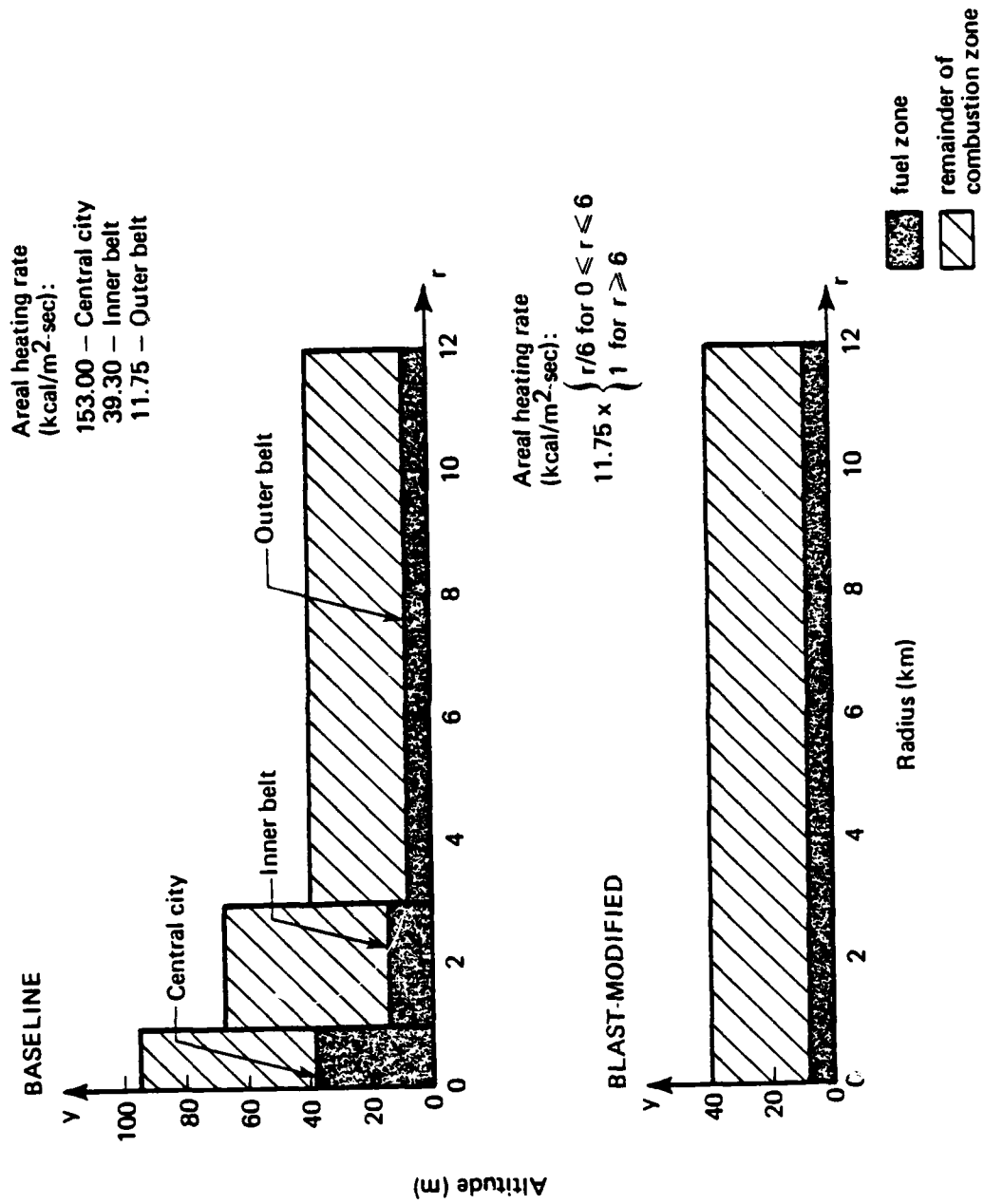


Fig. 25--Fire schematic for baseline and blast-modified city M

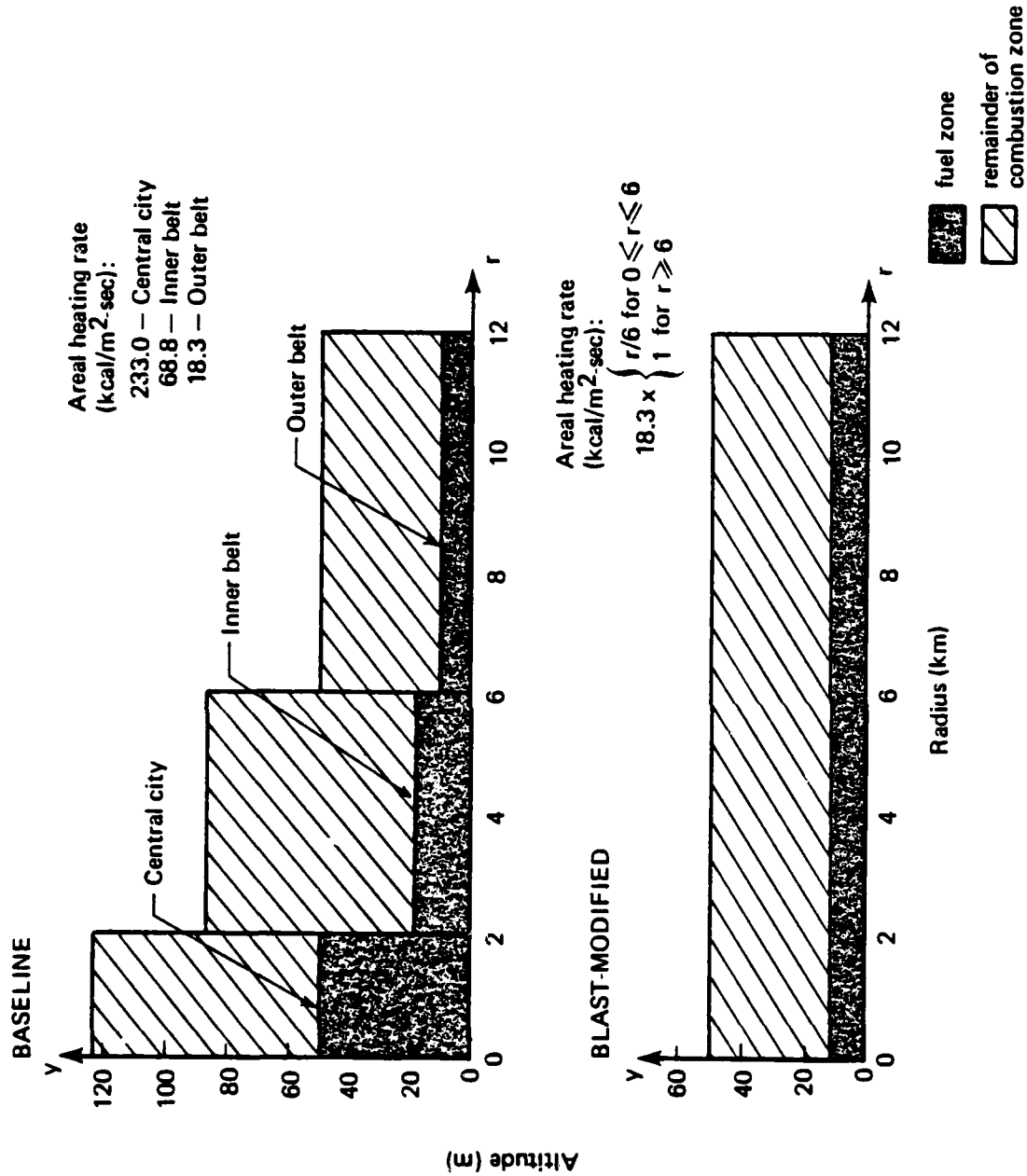


Fig. 26--Fire schematic for baseline and blast-modified city E

The baseline areal heating rates (see Figs. 24 through 26) for the central city, inner belt, and outer belt are estimated as follows. The average fuel loading per story L_s in each city region is defined in Table 7. The corresponding average total areal fuel loading L_T is then computed from

$$L_T = L_s \times N_s \times f_{Bu} , \quad (7)$$

with values for N_s and f_{Bu} taken from Table 6. The resulting total-loading estimates are also listed in Table 7. The central cities and outer belts are somewhat taller and shorter, respectively, than were those in the devastated Hamburg districts, and have higher and lower total loadings. The inner belts are defined to be on the order of the

Table 7
FUEL LOADING IN MODEL CITY REGIONS

Region	City		
	W	M	E
<i>Average Fuel Loading per Story, L_s^a (lb/ft²-story)</i>			
Central city	20	20	20
Inner belt	18	18	18
Outer belt	16	16	16
<i>Total Areal Fuel Loading, L_T (lb/ft²)</i>			
Central city	48.0	84.0	128.0
Inner belt	13.5	21.6	37.8
Outer belt	3.6	6.4	10.0

^aBased on DCPA [1973] estimates, which take into account both the structures and their contents.

Hamburg districts, but less built-up. Similarly, the inner-belt loadings tend to be somewhat less than the 32 lb/ft^2 estimated for Hamburg [DCPA, 1973].

Finally, in each model city region, the fire is assumed to consume 90 percent of the available fuel in 3 hr. The areal heating rate Q_A is thus computed from

$$Q_A = L_T \times \left(\frac{90\%}{3 \text{ hr}} \right) \times E_B, \quad (8)$$

with L_T taken from Table 7 and E_B , the average heat released per unit weight of combustibles, taken as [DCPA, 1973]

$$E_B = 8000 \text{ Btu/lb}. \quad (9)$$

For the blast-modified fire simulations represented in Figs. 24 through 26, the weapon burst is assumed to occur over the city center, leveling many buildings in the central city and inner belt. A centered, low-level burst of a 1 Mt weapon would produce such an effect, with blast damage extending out to radii on the order of 6 km (and fire to around 12 km) [Johnson and Larson, 1982]. The height of the fuel zone is thus simply assumed constant and equal to its outer-belt value in the baseline case. The total height of the combustion zone is chosen similarly.

The blast-modified areal heating rates are not considered independent of radius, however. In each case, the combustibles of the central city and inner belt would be spread radially to some degree by the blast, and piled up in a debris field. Since some combustibles in that zone may be buried under layers of nonflammable materials (e.g., concrete, brick, metal), the areal heating rate is not expected to be correspondingly higher, and may in fact be relatively small. We consider such a situation in each simulation. It is assumed that the areal heating rate is zero at the fire center, increases linearly with radius over the debris zone, and equals its baseline outer-belt value for radii greater than 6 km.

In each model city simulation, the required data set consists of the geometric parameters R and H , the heating rate parameters QH and $q(r, y)$, the radiation coefficient σ , and the turbulence coefficients M_1 and K_1 . Once R , H , and QH are chosen, the parameter A in Eqs. (1) is determined along with the radial velocity scale U from Eqs. (2).

In all cases, the fire radius R is taken to be 12 km. However, since the combustion zone height is not constant in the baseline cases, there are no natural choices for H . The values for H listed in Table 8

Table 8
PARAMETERS IN MODEL CITY SIMULATIONS

Parameter	City		
	W	M	E
<i>Fundamental Parameters</i>			
R (km)	12	12	12
H (m)	40	60	100
QH (kcal/m ² -sec)	9.50	14.25	23.75
<i>Auxiliary Parameters</i>			
U (m/sec)	33.6	33.6	33.6
A	0.347	0.521	0.868
σ	0.264	0.264	0.264
M_1, K_1	0.125	0.125	0.125

are arbitrarily selected as characteristic of the baseline geometry in Figs. 24 through 26. The values of the heating rate scale QH in Table 8 are chosen likewise.

Table 8 also lists the corresponding values of U and A , calculated using Eqs. (2).[†] From Eqs. (2) and (3), σ depends on H , QH , and the radiation mean free path k^{*-1} ; and M_1 depends on R , U , and the dimensional eddy viscosity \mathcal{E}_1/ρ_a . As in our earlier simulation

[†]The value of the dimensionless perturbation pressure scale δ is 1.44×10^{-2} for all cases.

(Part I), we take $k^{*-1} = 20$ m, $\xi_1/\rho_a = 5.04 \times 10^4$ m²/sec, and $M_1 = K_1$. The values we use for σ , M_1 , and K_1 [from Eqs. (2) and (3)] are also listed in Table 8.

Finally, we use the heating rate distributions $q(r, y)$ defined in Figs. 27 through 29. The heating rate is taken to be constant in the fuel zone of each baseline city region, and to decrease linearly with altitude over the remainder of the combustion zone, approaching zero at the top of that zone. Subject to the choices of QH in Table 8, the fuel zone values of $q(r, y)$ are selected so that the resulting areal heating rates

$$\int_0^{\infty} QH q(r, y) dy$$

are equivalent to those in Figs. 24 through 26. The blast-modified forms of $q(r, y)$ are developed likewise.

SIMULATION RESULTS

The results of the model city simulations are summarized by Table 9, which compares predicted baseline and blast-modified velocity, temperature, and pressure maxima. As expected, the predictions for the baseline simulations are all larger than those for the blast-modified simulations. The differences are great for the temperature, pressure, and vertical velocity maxima, but small for the radial velocity maxima (10 percent or less). Therefore, the winds and wind damage resulting from nuclear-weapon-ignited fires may be relatively insensitive to the degree of blast disruption of the fuel bed.

In any case, the predictions in Table 9 indicate that the winds generated by a large urban fire will in themselves constitute a major threat. Although most of the velocities in the table are less than hurricane force (more than 30 m/sec), it should be noted that those values represent *means*. Near street level, where fire winds will be channeled between buildings, wind speeds of hurricane force should

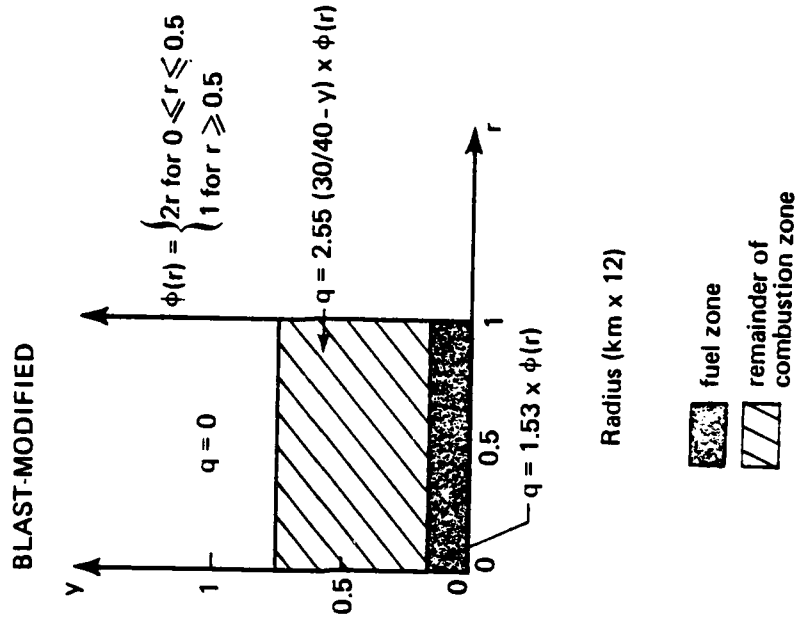
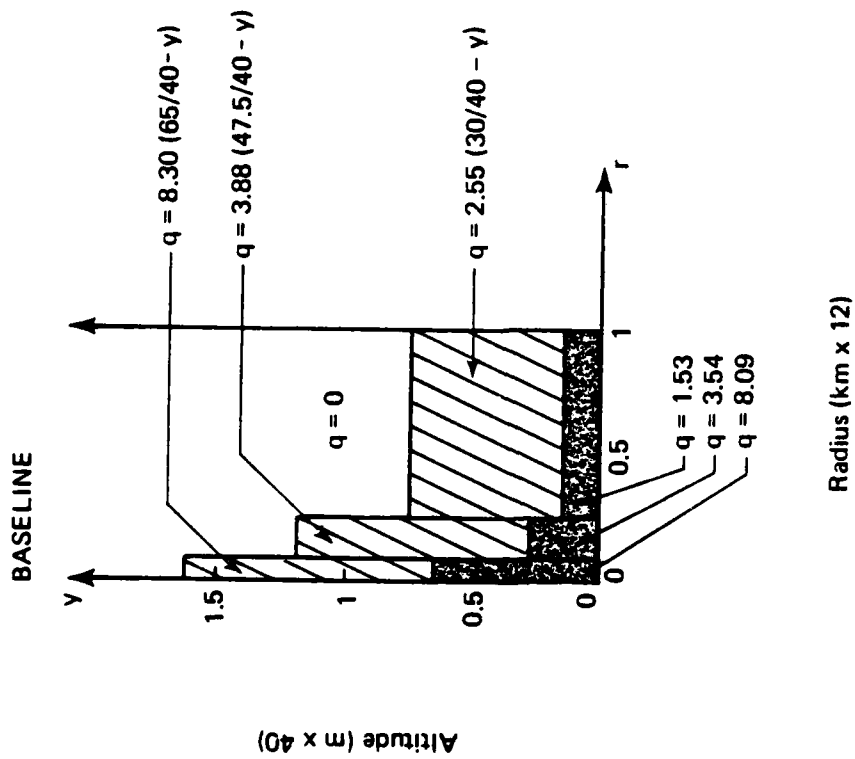


Fig. 27--Baseline and blast-modified heating rate spatial distributions for city W

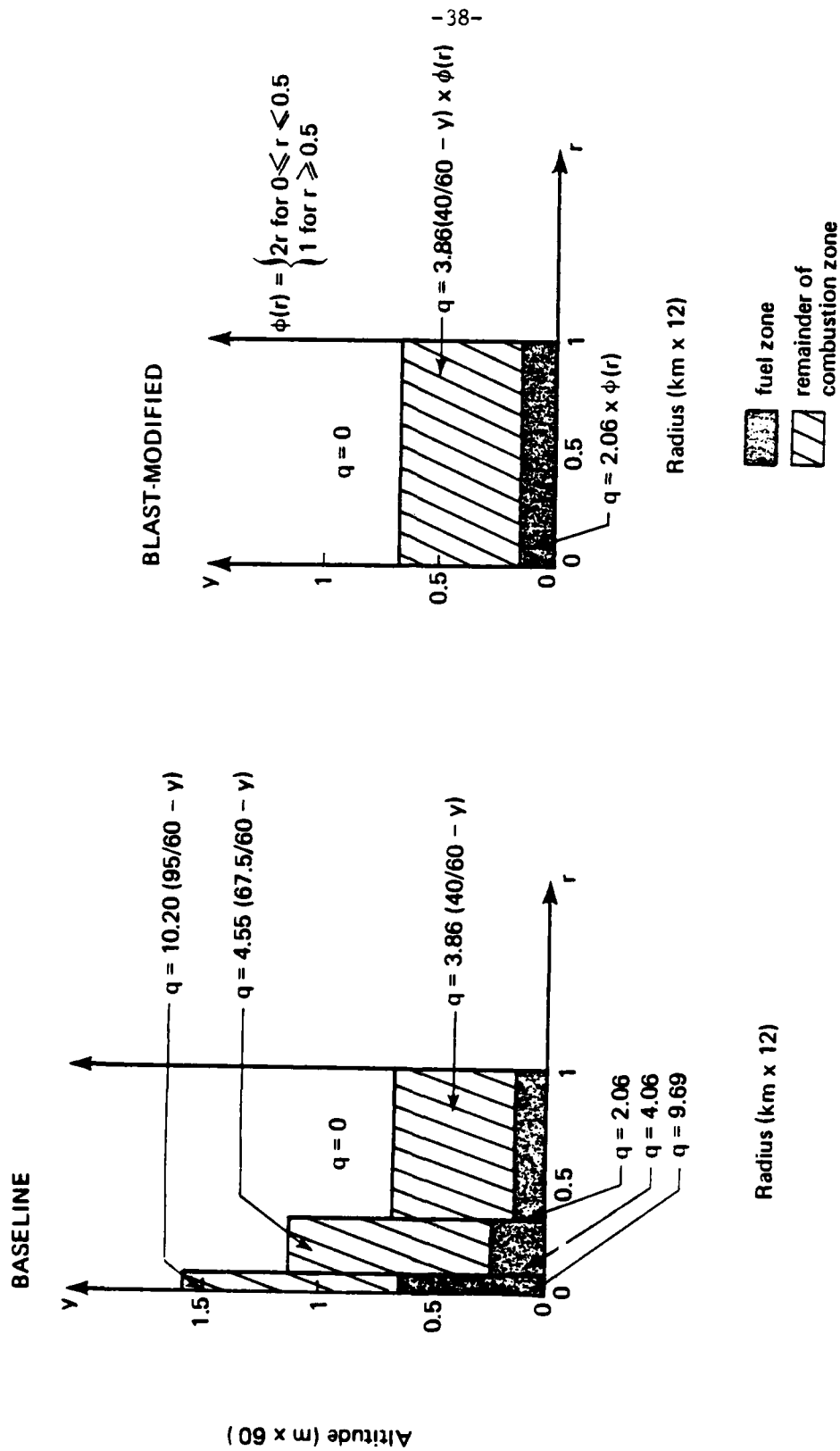


Fig. 28--Baseline and blast-modified heating rate spatial distributions for city M

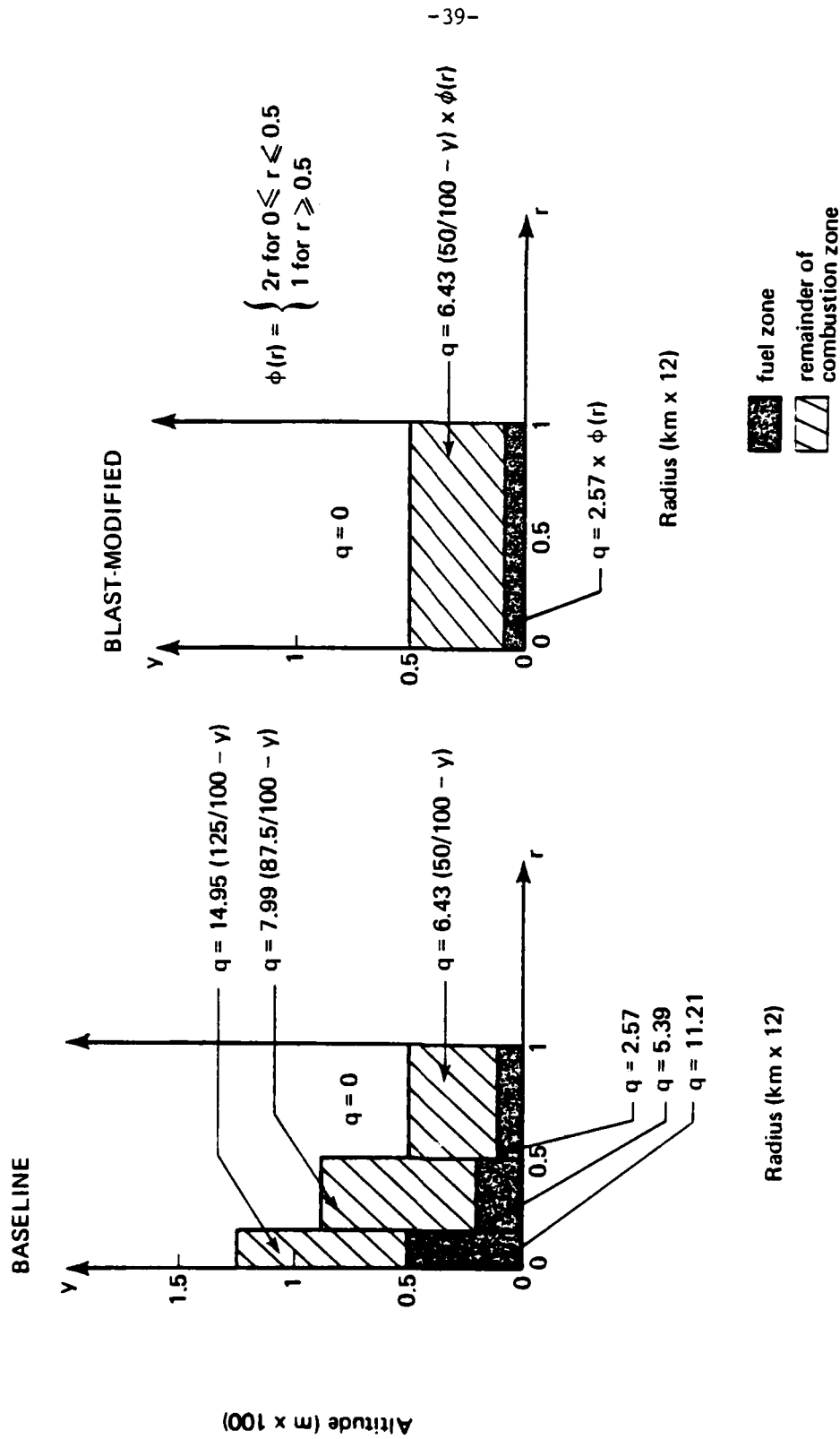


Fig. 29--Baseline and blast-modified heating rate spatial distributions for city E

Table 9

VELOCITY, TEMPERATURE, AND PERTURBATION PRESSURE
MAXIMA IN MODEL CITY SIMULATIONS

Simulation	City		
	W	M	E
<i>Maximum Radial Velocity, u_{max} (m/sec)</i>			
Baseline	20.2	26.3	39.0
Blast-Modified	17.9	23.9	28.5
<i>Maximum Temperature, T_{max} ($^{\circ}K$)</i>			
Baseline	577	619	704
Blast-Modified	455	485	510
<i>Maximum Perturbation Pressure, P_{max} (psi)</i>			
Baseline	0.056	0.113	0.271
Blast-Modified	0.011	0.044	0.076
<i>Maximum Vertical Velocity, v_{max} (m/sec)</i>			
Baseline	0.89	3.12	12.48
Blast-Modified	0.37	1.56	4.32

be considered typical. The winds may be even greater than those encountered in the Hamburg firestorm of 1943 (see Part I).

Also as expected, the velocity, temperature, and pressure predictions in Table 9 are all greatest for city E (the tallest and densest) and least for city W (the shortest and sparsest). For a given fire, therefore, the threat will be most severe for the most congested cities. In general, however, the shorter cities sprawl out over greater areas than do taller ones of comparable population, and are thus capable of supporting more widespread fires. Multiple weapon bursts can greatly increase the fire severity in such cities.

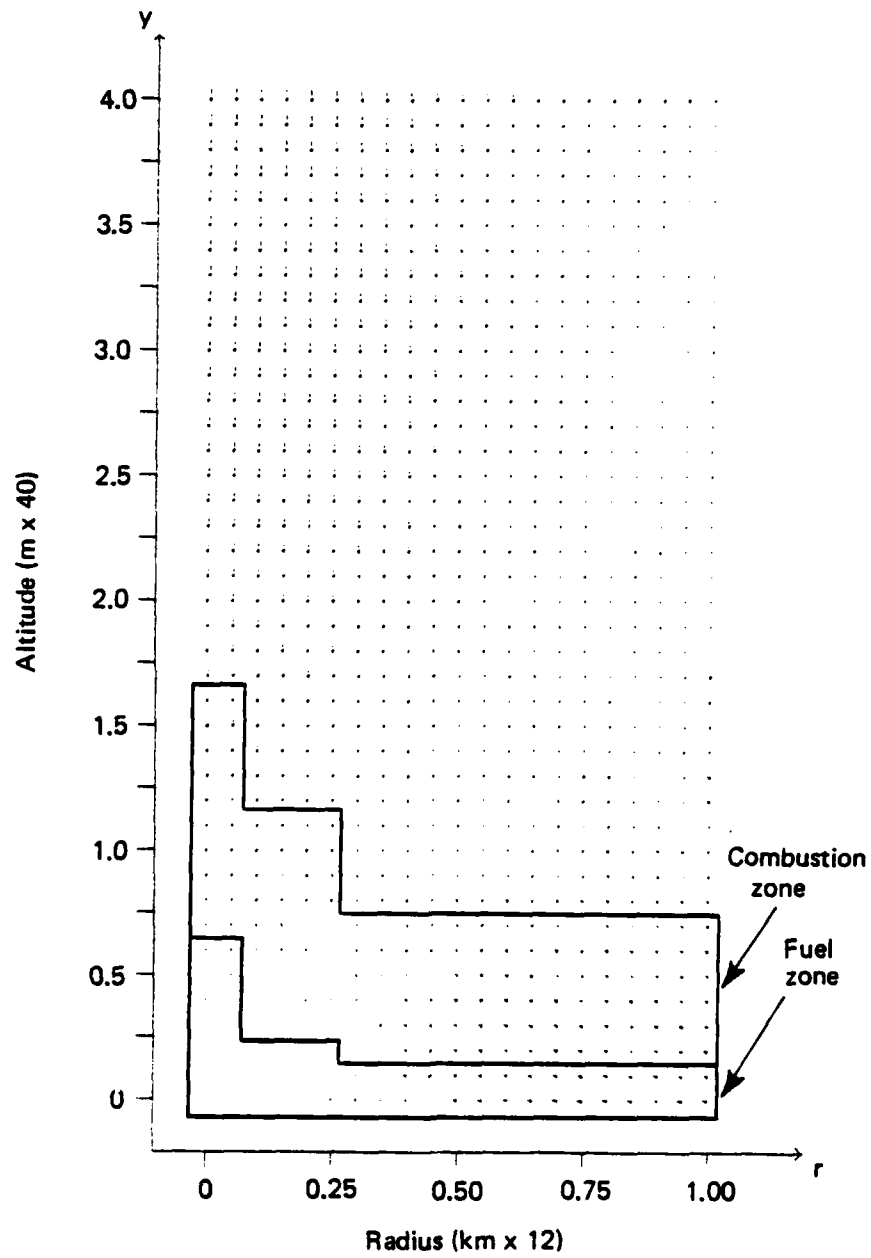
In the remainder of this subsection, we describe the results of the model city simulations in more detail. The vector plot

in Fig. 30 is representative of the flow fields obtained in the simulations. The flow in each case is everywhere inward (toward the symmetry axis) and upward, with the horizontal velocity typically maximum on the symmetry axis in the upper portion of the turning region. Figures 31 through 34 present, respectively, the temperature and pressure contours and radial and vertical velocity profiles for baseline and blast-modified simulations for city W. Similar sets of plots for cities M and E are presented in Figs. 35 through 38, and 39 through 42, respectively.

As expected (cf. Fig. 12), the baseline and blast-modified temperature contours in Fig. 31 are quite different. In the baseline case, the heat release is greatest at the center of the fire (see Fig. 27) and the temperature is maximum on the symmetry axis. At any fixed altitude, the variation of temperature with radius is roughly Gaussian. However, in the blast-modified case, the temperature maximum does not occur on the symmetry axis. Rather, since the heat release is greatly diminished and actually least in the fire center (Fig. 27), the temperature is maximum about halfway between the center and the periphery. Additionally, the temperature is uniformly reduced in the blast-modified case.

Figures 32 through 34 show little qualitative difference between the baseline and blast-modified pressures and velocities. The contour plots in Fig. 32 exhibit the same behavior, the pressure drop decreasing with an increase in either radius or altitude. Likewise, the profile plots in both Figs. 33 and 34 are qualitatively the same. The radial velocity is maximum at ground level on the periphery and the vertical velocity is maximum on the symmetry axis in the upper part of the turning region. At any specified altitude, the variation of vertical velocity with radius is again roughly Gaussian. Of course, as expected, certain quantitative differences are evident: pressure drops and velocities are all less in the blast-modified case than in the baseline case. However, the radial velocity differences are relatively small.

The comparisons in both Figs. 35 through 38 and Figs. 39 through 42 are similar to those in Figs. 31 through 34. The primary difference



Source: From calculation for baseline city W.

Fig. 30--Typical velocity field in model city simulations

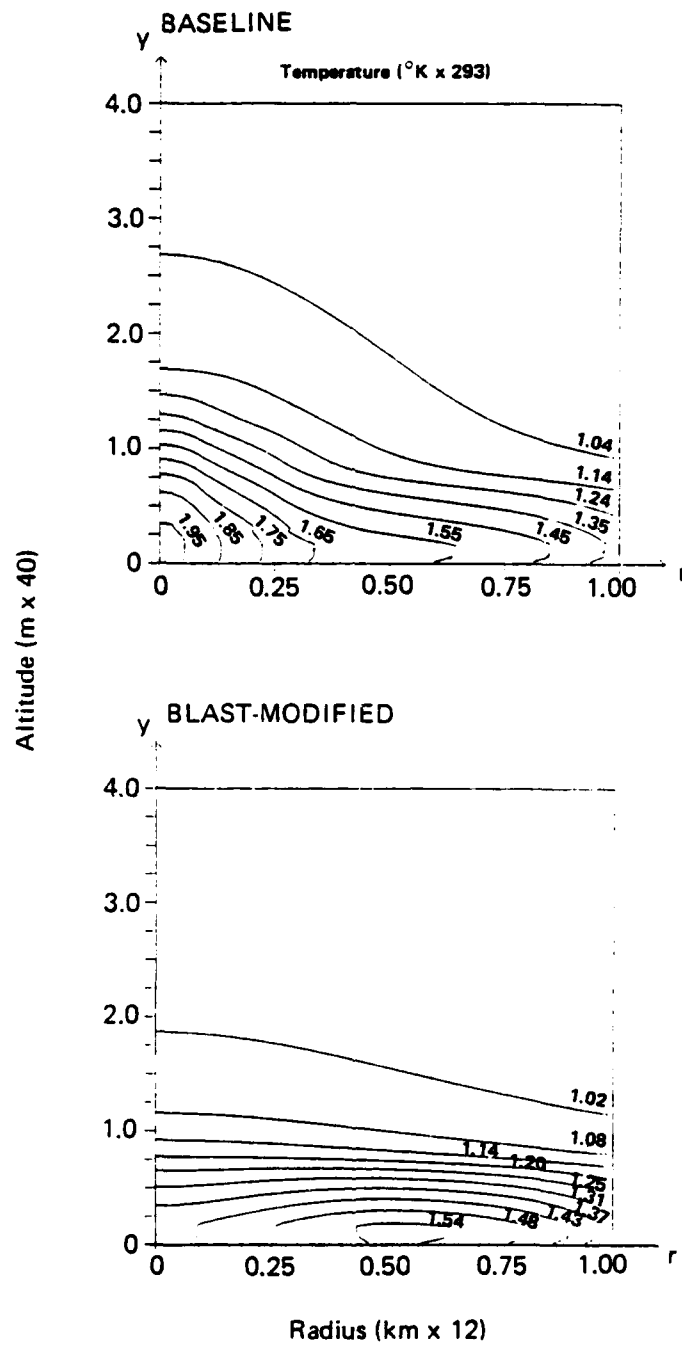
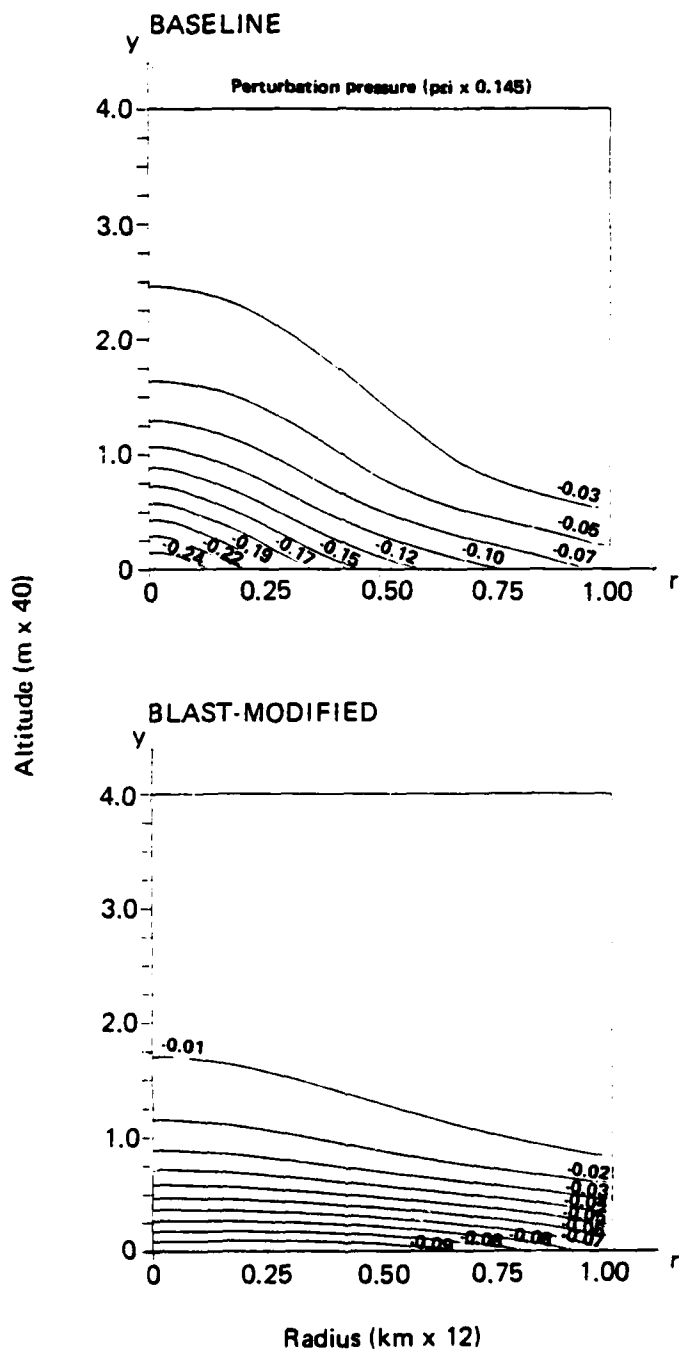


Fig. 31--Baseline and blast-modified temperature contours
for city W



Note: Perturbation pressure is $\delta P_s (P + A y)$; see footnote † on p. 6.

Fig. 32--Baseline and blast-modified pressure contours
for city W

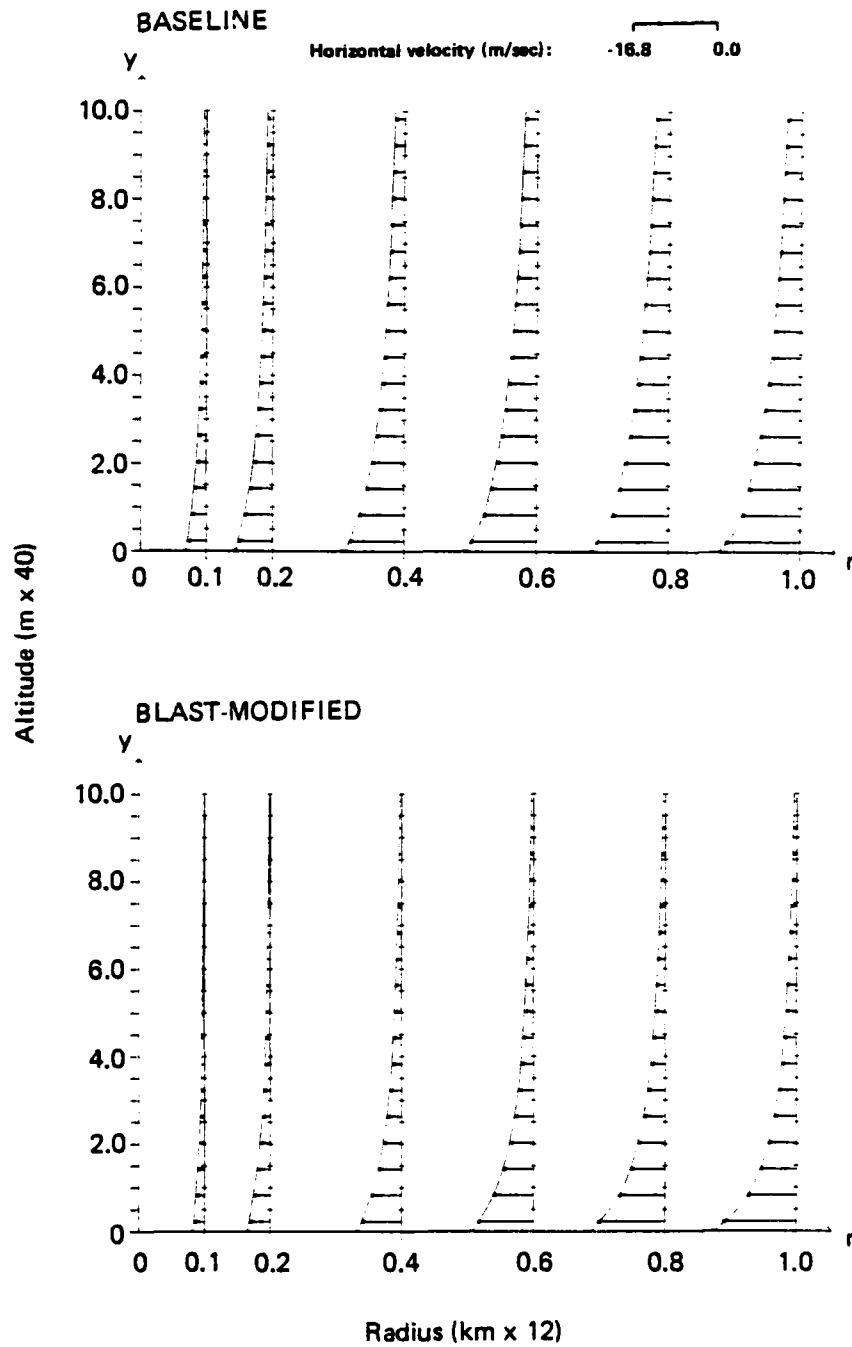


Fig. 33--Baseline and blast-modified radial velocity profiles for city W

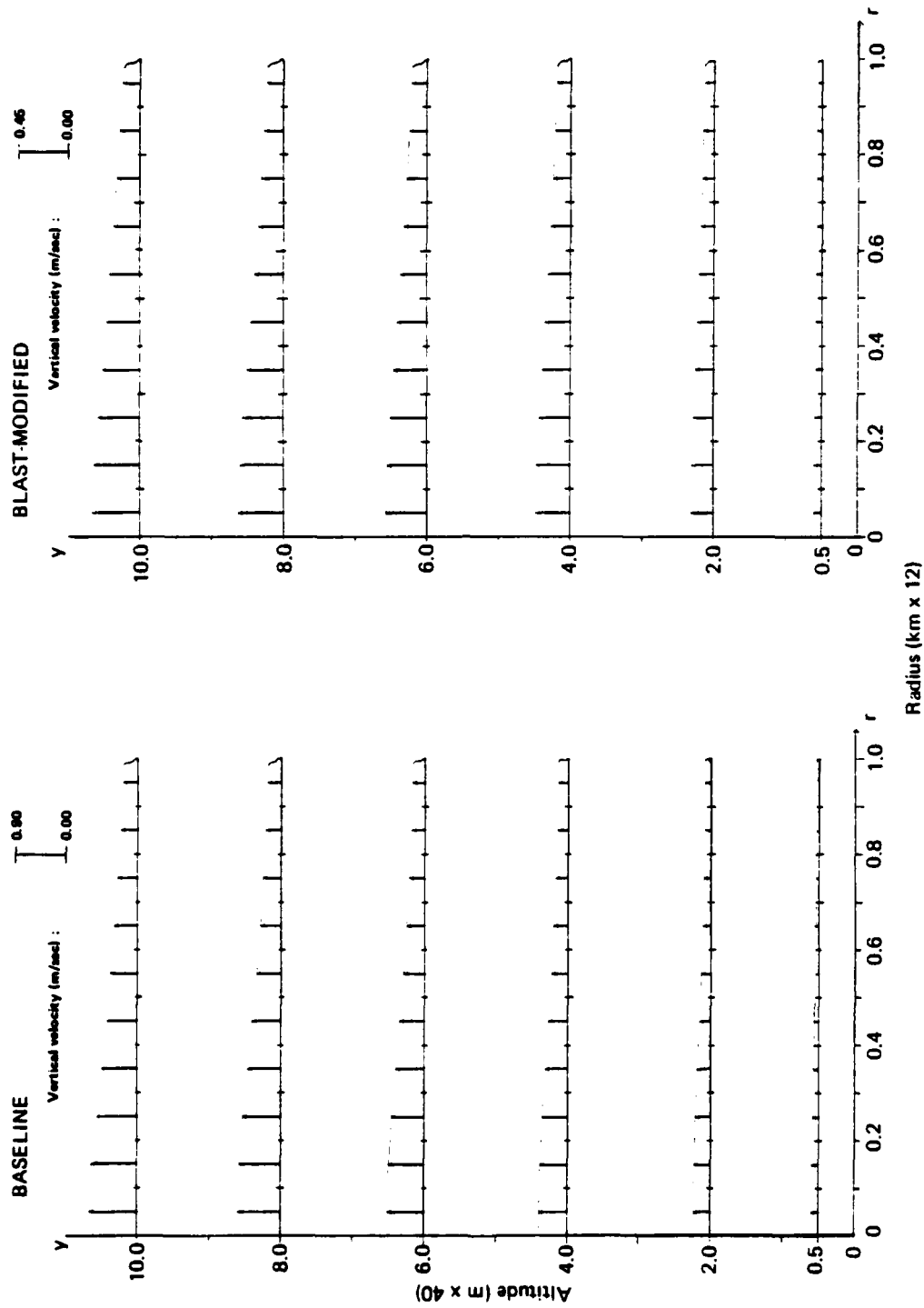


Fig. 34--Baseline and blast-modified vertical velocity profiles for city W

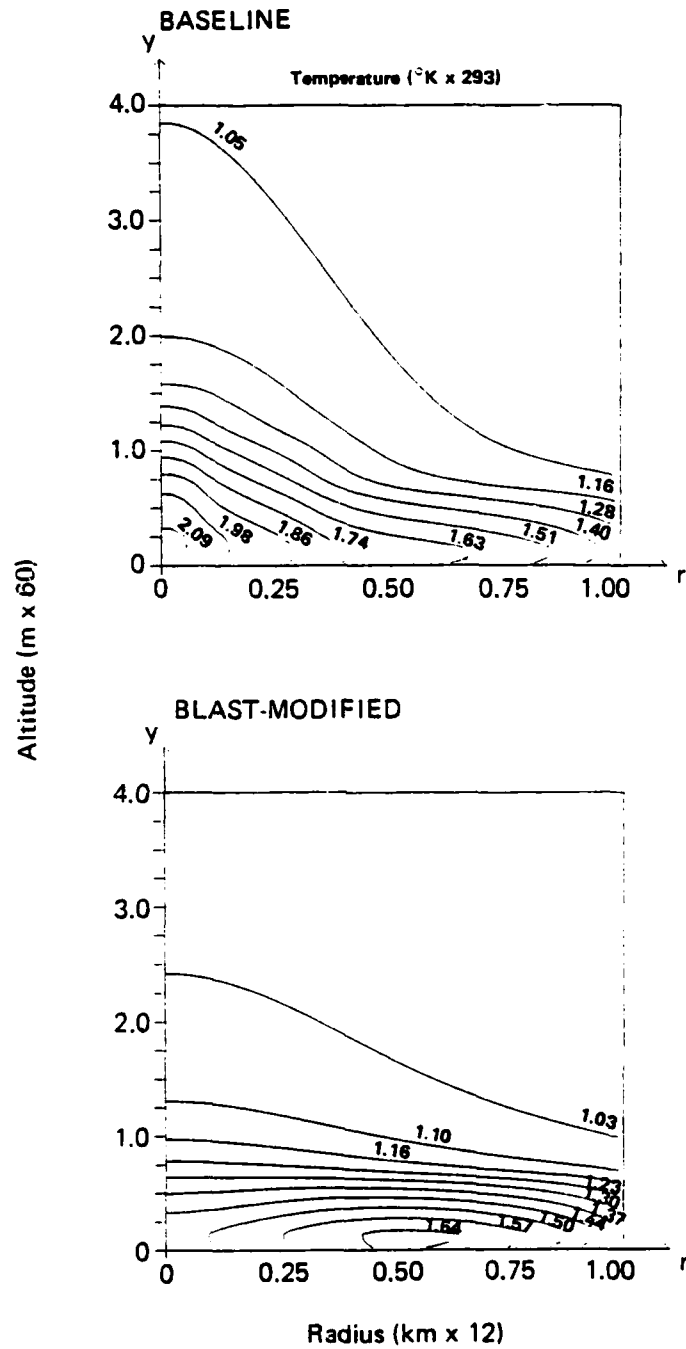
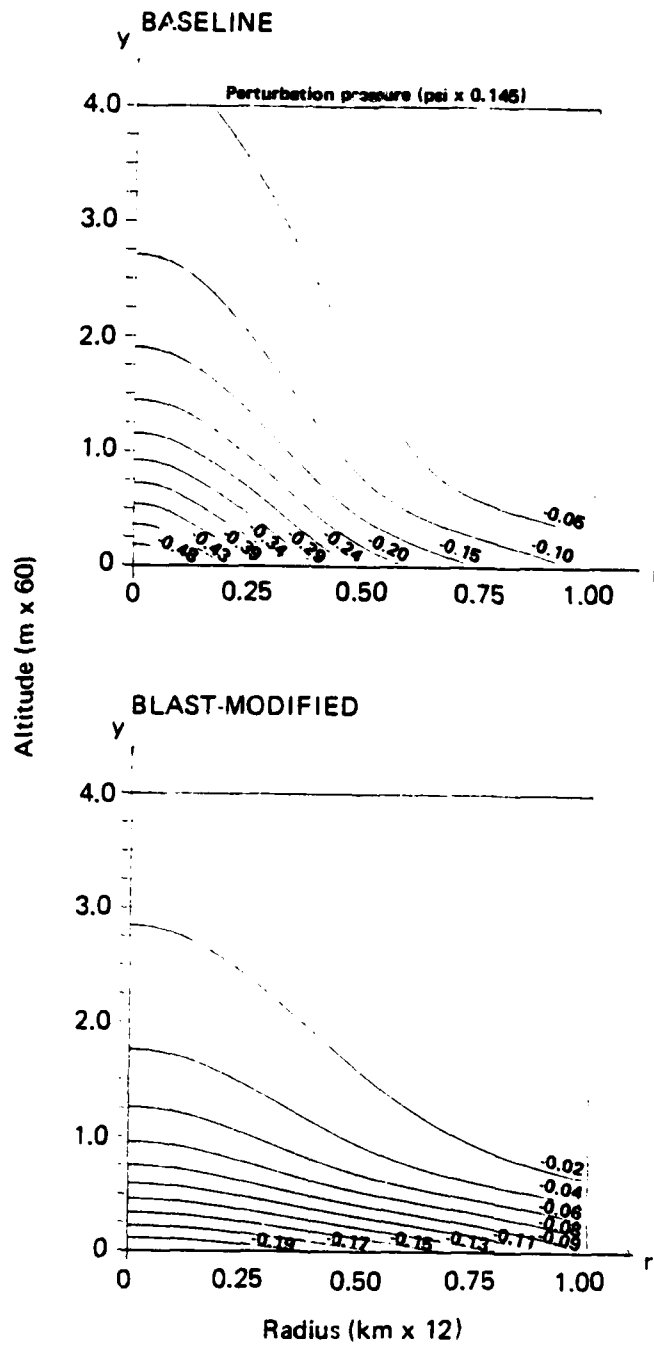


Fig. 35--Baseline and blast-modified temperature contours for city M



Note: Perturbation pressure is $\delta P_g(P + A\gamma)$; see footnote † on p. 6.

Fig. 36--Baseline and blast-modified pressure contours
for city M

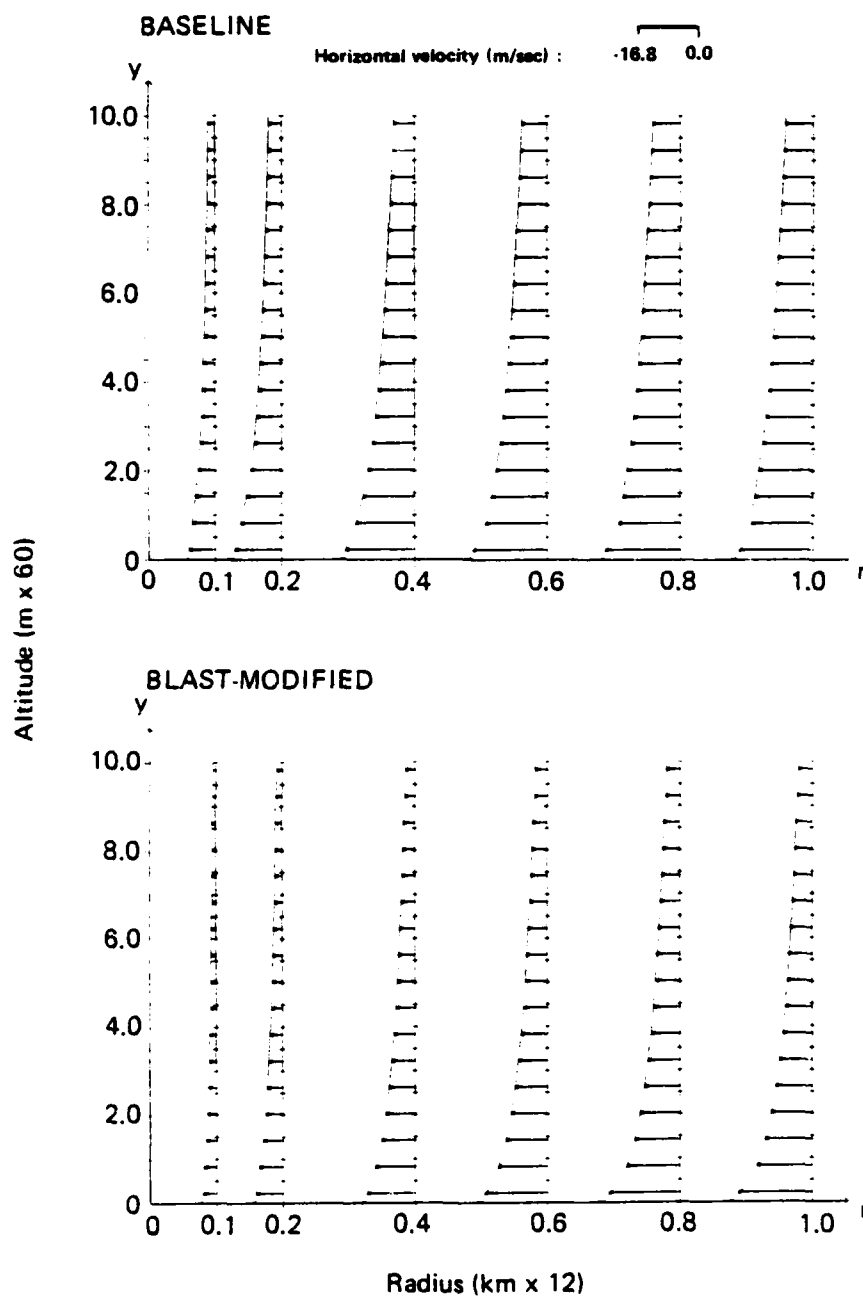


Fig. 37--Baseline and blast-modified radial velocity profiles for city M

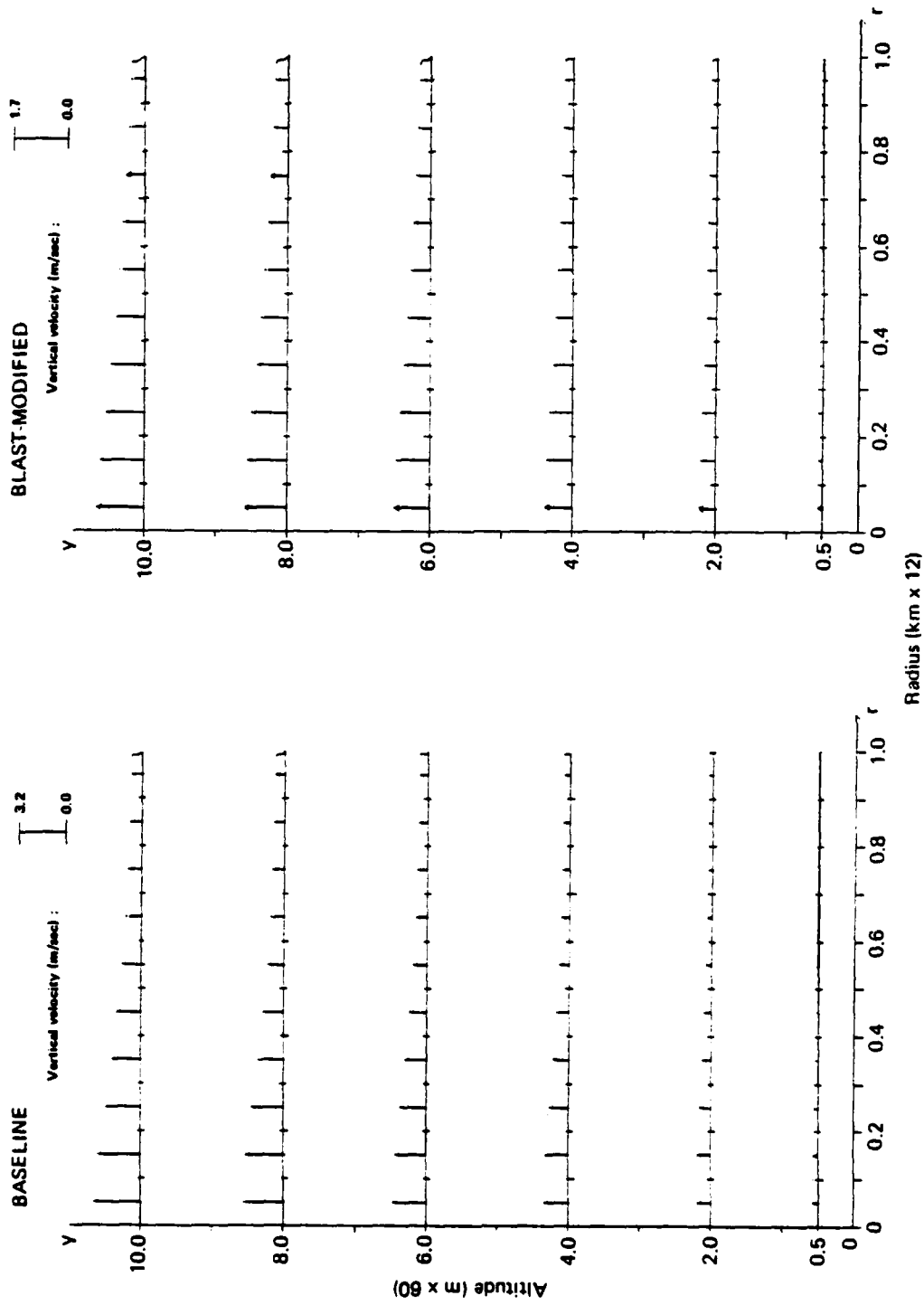


Fig. 38--Baseline and blast-modified vertical velocity profiles for city M

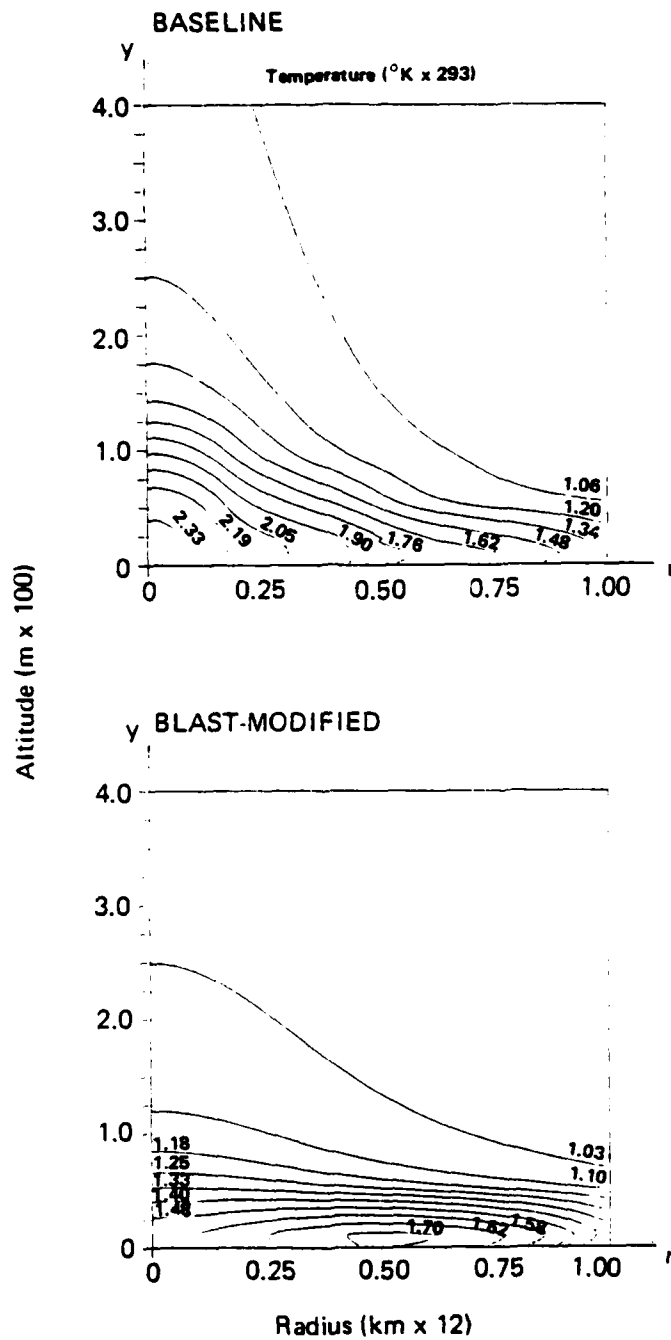
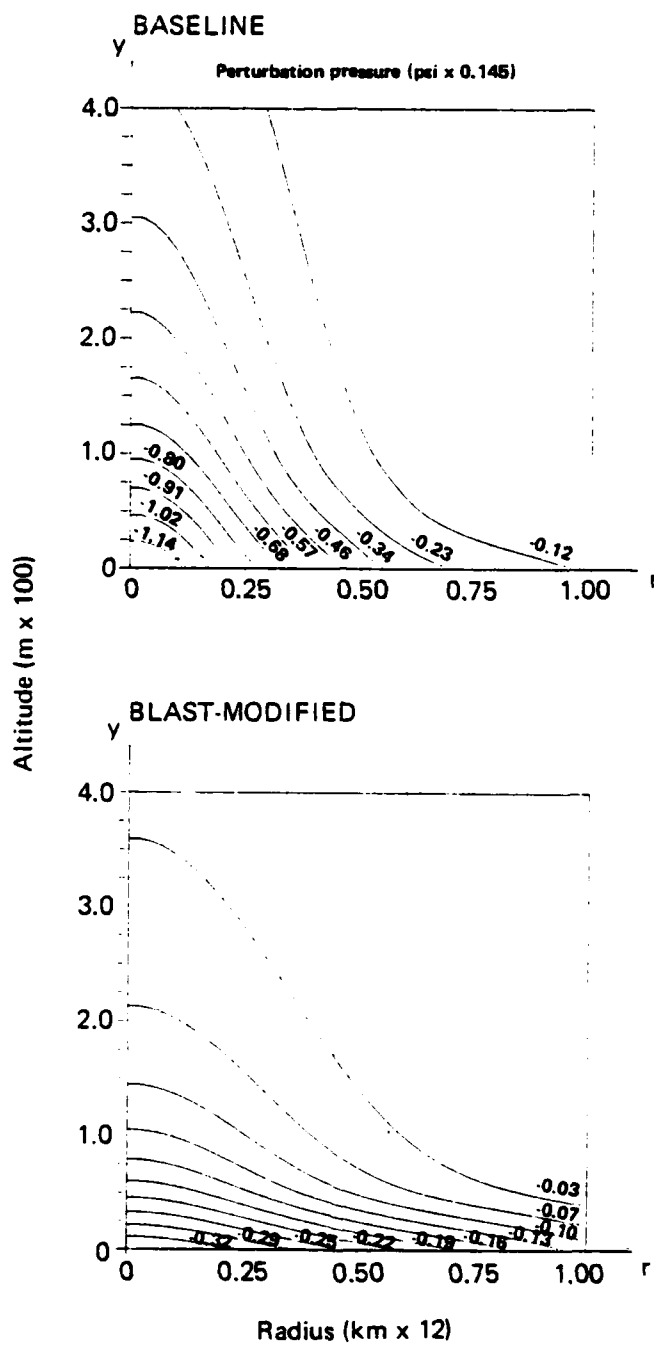


Fig. 39--Baseline and blast-modified temperature contours for city E



Note: Perturbation pressure is $\delta P_g(P + Ay)$; see footnote † on p. 6.

Fig. 40--Baseline and blast-modified pressure contours
for city E

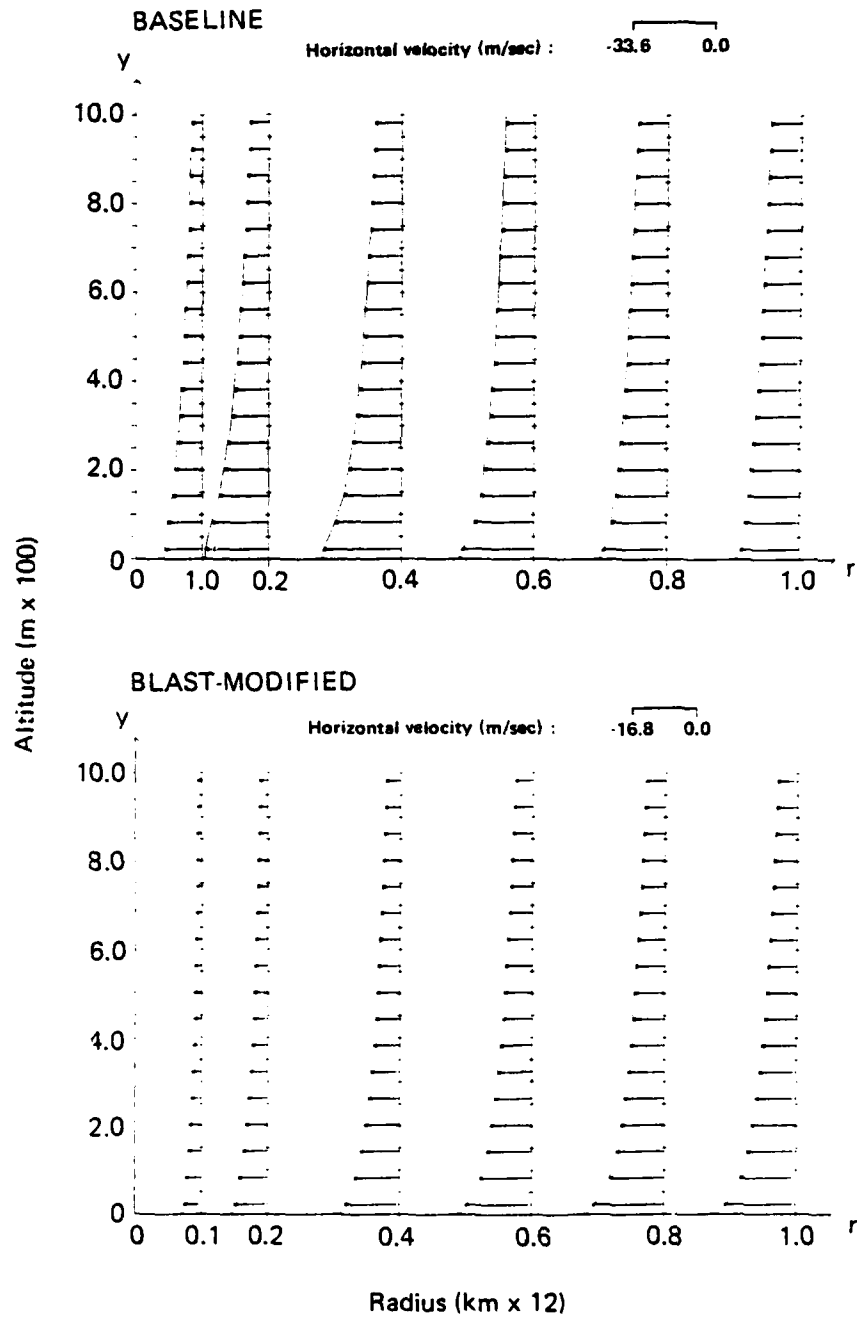


Fig. 41--Baseline and blast-modified radial velocity profiles for city E

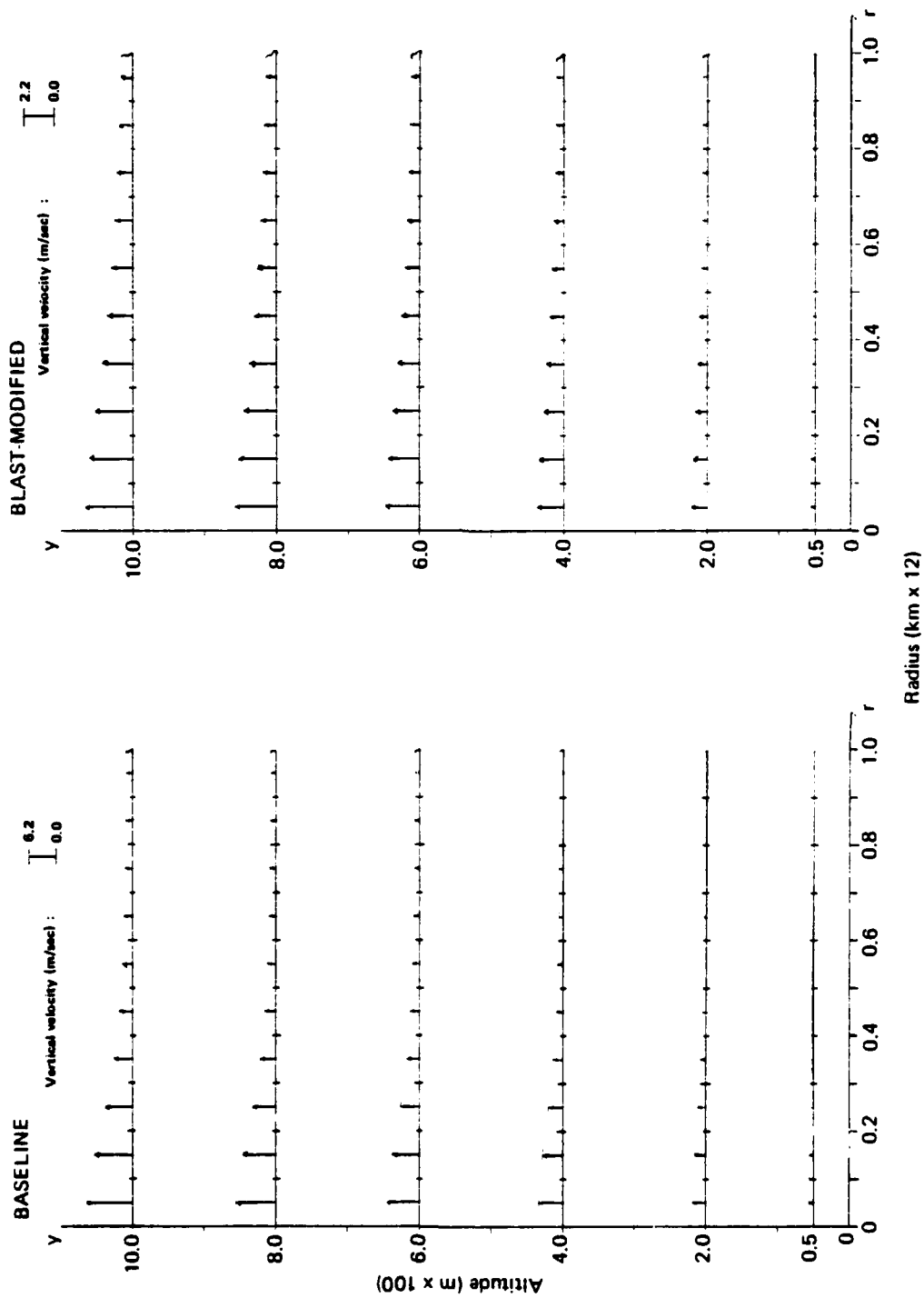


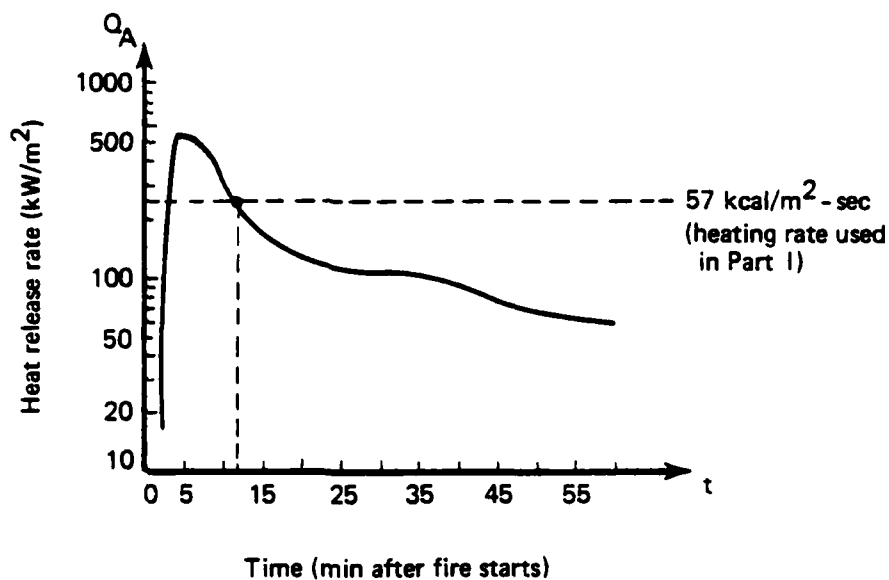
Fig. 42--Baseline and blast-modified vertical velocity profiles for city E

in the results presented in the corresponding plots is that temperatures, pressure drops, and velocities all increase with total loading, and are least for city W and greatest for city E. Further, as shown in Fig. 41, the baseline radial velocity for city E is not maximum at the fire periphery, as in the other cases (cf. Figs. 33 and 37), but rather about halfway between the periphery and the center. That difference presumably reflects the greater radial extent of the taller central-city and inner-belt regions in this case than in the others (cf. Figs. 27 through 29).

IV. SAMPLE TIME-DEPENDENT SIMULATION

This section extends the quasi-steady turning-region analysis of Part I to obtain time-dependent predictions. The multiple-fuel-bed Flambeau fire [Countryman, 1969; Palmer, 1981] treated in Part I is used as a sample case.

Figure 43 presents a typical time-history of the areal heat release in the largest Flambeau fires. During the period encompassing most of the burning (5 to 55 min after the fire starts), variations in the mean heat release rate occur on a time scale of many minutes. At any given point during that period, a steady-state analysis like that in Part I (Sec. IV) is justified as long as dynamic transients occur on a much shorter time scale of, say, a minute or less. As we now show, that criterion is satisfied at all times between 5 and 45 min. A time-dependent simulation is constructed by performing steady-state calculations at several points in that interval.



Source: Adapted from Fig. 3 of Palmer [1981]. Reprinted with permission from *Atmospheric Environment*, Vol. 15, Thomas Y. Palmer, "Large Fire Winds, Gases and Smoke," 1981, Pergamon Press, Ltd.

Fig. 43--Areal heat release time-history for Flambeau fire 760-12

In the steady-state Flambeau simulation, we used $R = 250$ m, $H = 20$ m, $QH \sim 50 \text{ kcal/m}^2\text{-sec}$, and hence had $U \sim 8 \text{ m/sec}$ [see Eqs. (2)]. For that case, the time scale R/U on which dynamic transients occurred was approximately 30 sec, satisfying the criterion for the flow to be quasi-steady. In the new, time-dependent analysis, we similarly use

$$\begin{aligned} R &= 250 \text{ m} , \\ H &= 20 \text{ m} , \end{aligned} \tag{10}$$

but vary QH with time as shown in Fig. 43. At any given time, the criterion for the flow to be quasi-steady is that $QH \gtrsim 25 \text{ kcal/m}^2\text{-sec}$. From Fig. 43, it is certainly satisfied for periods between 5 and 45 min, and possibly up to 55 min as well.

In the following simulation, we calculate quasi-steady flows at points 5 min apart. The specific values of QH used at those points are summarized in Table 10. As in the steady-state simulation of Part I, we also use

$$q(r, y) = \begin{cases} 1.6 & \text{for } 0 \leq y \leq 0.25 \\ 1.6 \left(\frac{4}{3} (1 - y) \right) & \text{for } 0.25 \leq y \leq 1.0 , \\ 0 & \text{for } y \geq 1.0 \end{cases}$$

$$k^{*-1} = 20 \text{ m} ,$$

$$\frac{\xi_1}{\rho_a} = \frac{k_1}{c_p \rho_a} = 8410 \text{ m}^2/\text{sec} \tag{11}$$

at each point. Thus, from Eqs. (2) and (3),

$$U = 8.41 \times F \quad \text{m/sec} ,$$

$$A = \frac{2.77}{F^2} ,$$

$$\sigma = \frac{0.022}{F} ,$$

$$M_1 = K_1 = \frac{4.0}{F} , \quad (12)$$

where

$$F = \frac{QH}{57 \text{ kcal/m}^2\text{-sec}} \quad (13)$$

and, from p. 6, $\delta = 9.04 \times 10^{-14} \times F^2$.

Figures 44 through 47 summarize the results of the time-dependent Flambeau simulation. The predicted variations with time of the temperature, pressure, and velocity fields are shown for the heat release described in Fig. 43. The solid curves represent the results of the quasi-steady analysis, which is considered appropriate for the period approximately 5 to 55 min after the fire starts.

Table 10

HEAT RELEASE SCALES USED IN TIME-DEPENDENT FLAMBEAU SIMULATION

Time (min)	QH (kcal/m ² -sec)
5	134
10	84
15	53
20	38
25	31
30	24
35	20
40	18
45	18
50	14
55	10

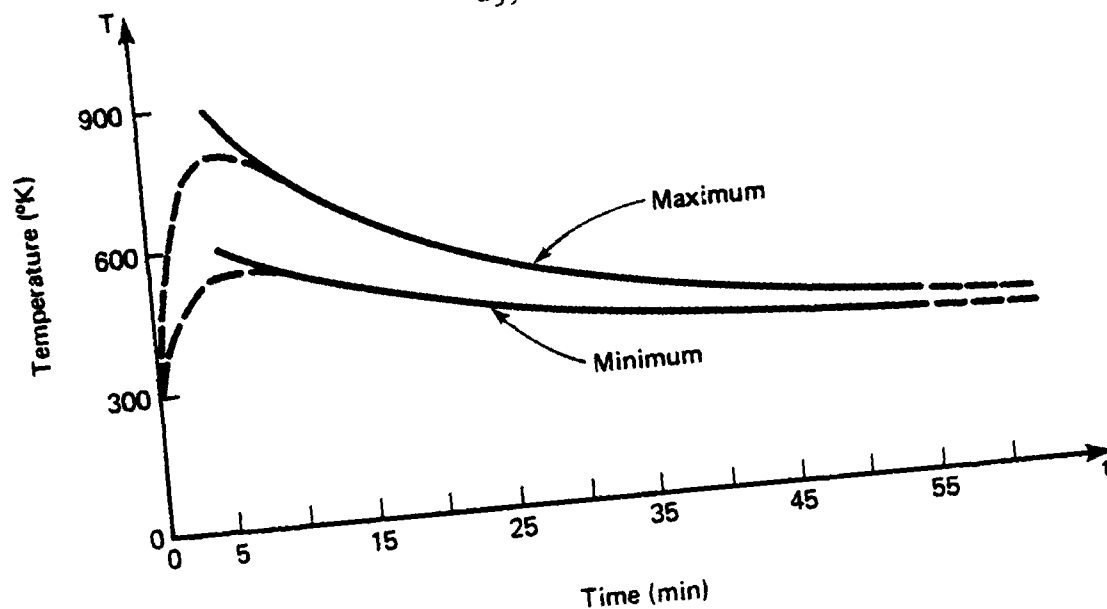


Fig. 44--Time-history of maximum and minimum combustion zone temperatures for sample Flambeau fire

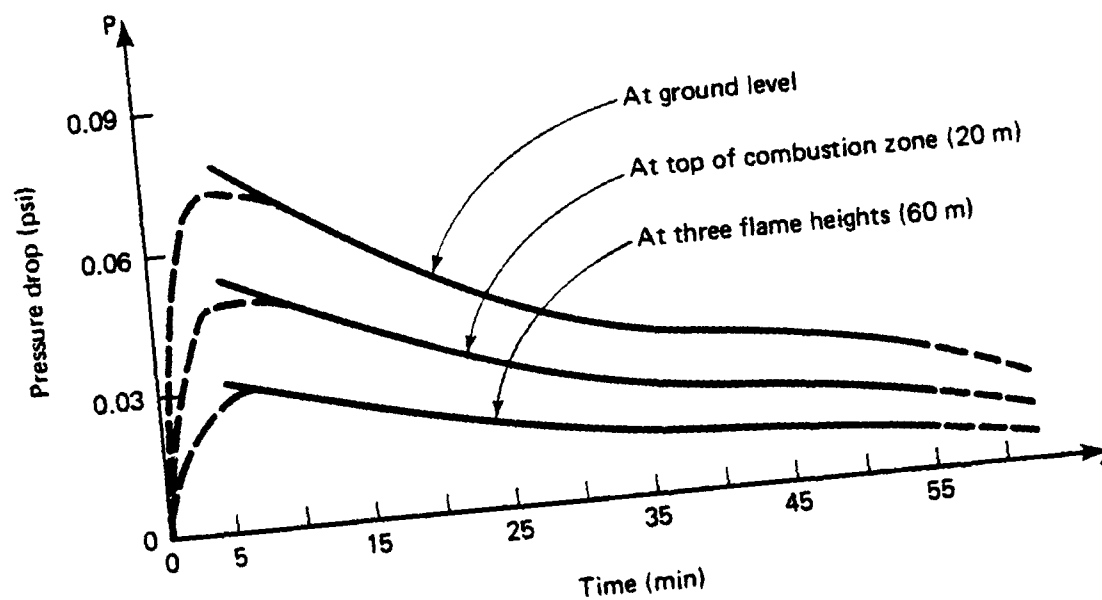


Fig. 45--Time-history of peripheral pressure drop for sample flambeau fire

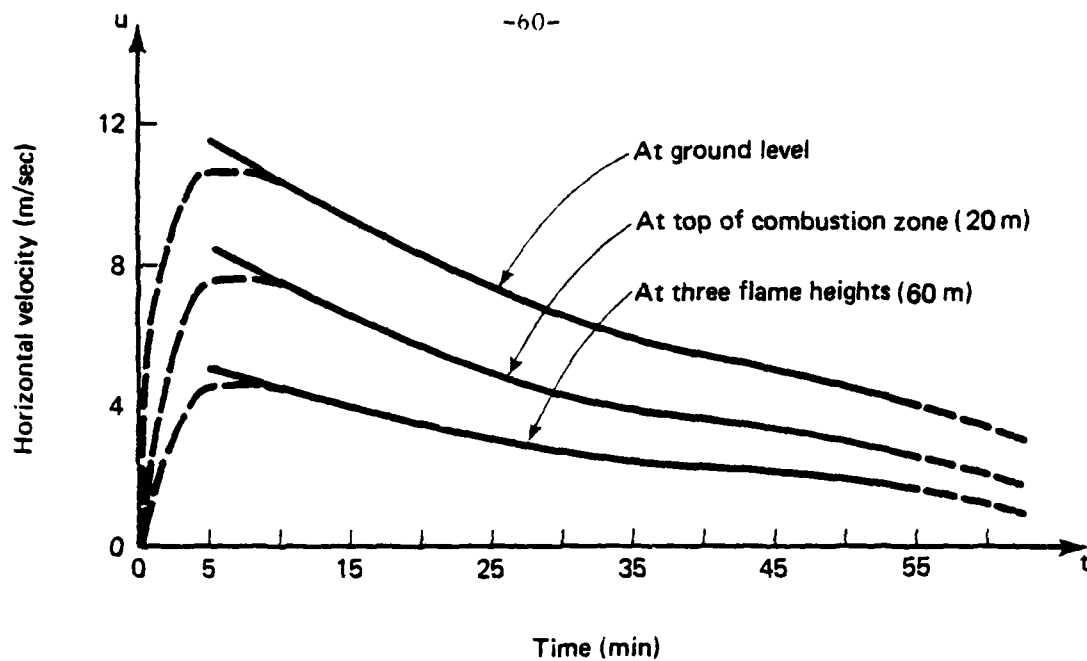


Fig. 46--Time-history of induced peripheral fire wind (radial velocity) for sample Flambeau fire

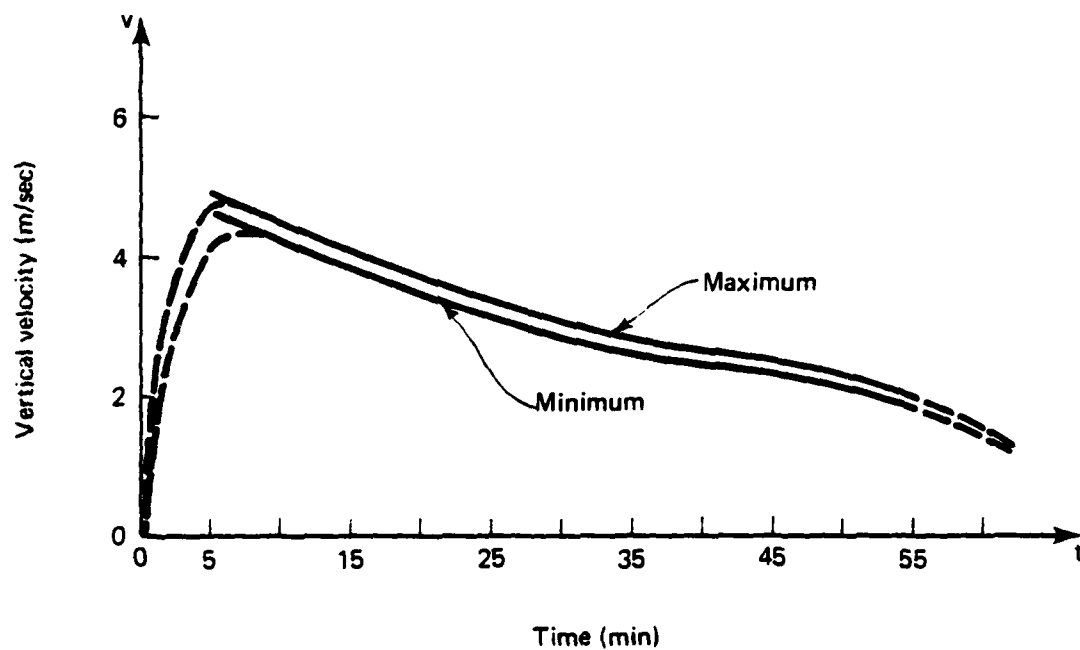


Fig. 47--Time-history of emerging column flow (vertical velocity at top of turning region) for sample Flambeau fire

During the first 5 min of burning, when the individual fires are coalescing to form a large-fire system, the heat release rate (Fig. 43) is changing on a time scale that is fairly fast compared with that for convection. The same is also true during the final phase of fire activity, i.e., the period later than 1 hr or so when the large fire begins to disintegrate and burn out. For those two periods, the quasi-steady analysis is thus inappropriate, and the dashed curves in Figs. 44 through 47 illustrate the expected results of a more rigorous analysis.

Figure 44 describes the predicted variation of the temperature field with time in the burning zone. The contours shown in Fig. 48 are representative of the temperature field at any given time. Maximum temperatures occur in the center of the fire just above the top of the fuel zone (height ≈ 4 m). Minimum temperatures occur on the periphery at the top of the burning region. As expected, the time-histories of those temperatures resemble the heat release time-history shown in Fig. 43. Temperatures are everywhere greatest about 5 min after the fire starts, when the heat release is greatest, and then decrease with time.

The corresponding pressure and velocity time-histories shown in Figs. 45 through 47 follow the same pattern. As illustrated in Figs. 49 and 50, pressure gradients and radial velocities at any given time are maximum at the fire periphery. At all times, they are greatest at ground level and decrease with altitude. Finally, Fig. 47 characterizes the variation with time of the vertical velocity emerging at the top of the computational region (10 flame heights, 200 m). As illustrated in Fig. 51, velocity profiles at that height are almost top-hat at all times. Maximum and minimum velocities, which occur above the fire center and on the periphery, respectively, are thus always quite similar.

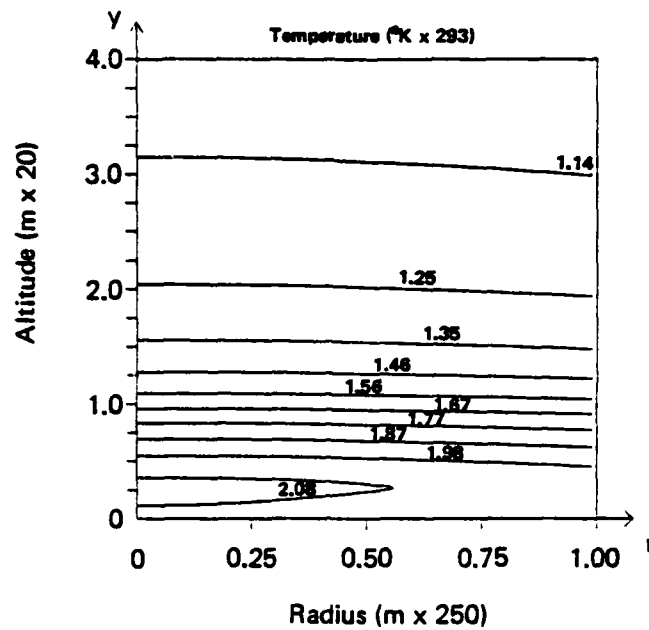
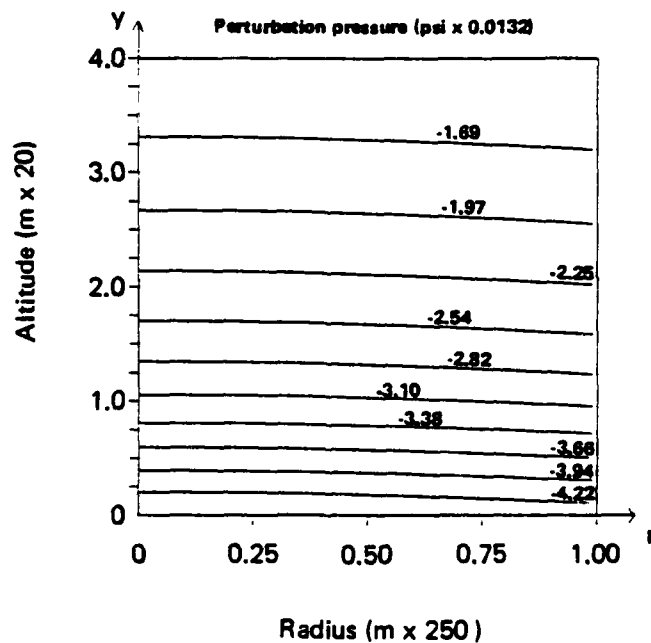


Fig. 48--Temperature contours after 15 min for sample Flambeau fire



Note: Perturbation pressure is $\delta P_g (P + A_y)$; see footnote † on p. 8.

Fig. 49--Pressure contours after 15 min for sample Flambeau fire

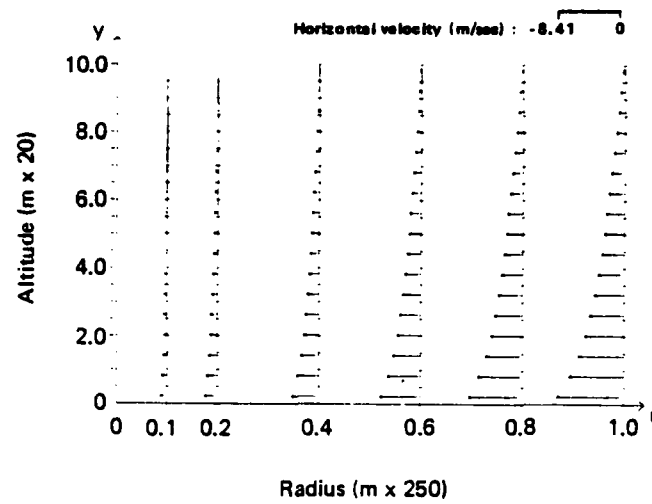


Fig. 50--Radial velocity profiles after 15 min for sample Flambeau fire

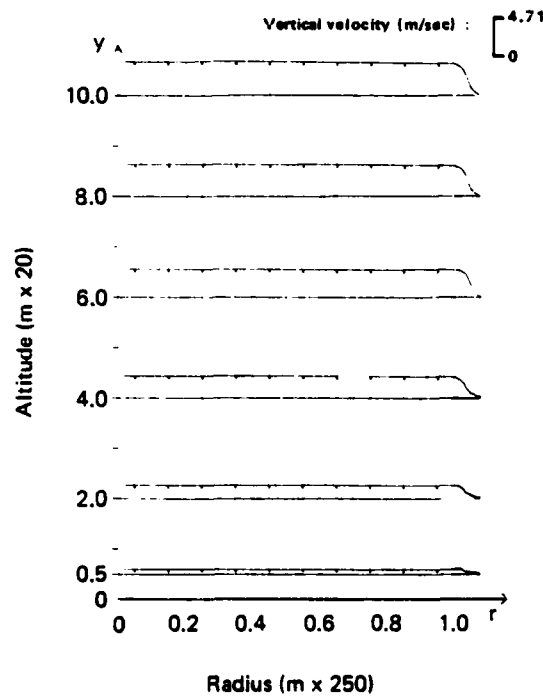


Fig. 51--Vertical velocity profiles after 15 min for sample Flambeau fire

V. DISCUSSION

In presenting calculations of the urban fire environment that may result from a nuclear weapon burst, our aim has been to describe the macroscopic features of a large area fire through analysis of the interactions that produce high temperatures and fire winds. Our approach has been to develop a model based on first principles. In contrast to asymptotic theories that extrapolate the properties of a free-convection plume, we consider the fire region directly. Despite our use of several simplifications and empiricisms, we expect that the theory yields a fine resolution of the hydrothermodynamics of a large area fire.

The analysis considers a quasi-steady axisymmetric fire in an urban area. A spatially dependent volume-heat-release function is used to describe the energy input from fires in a blast-disturbed urban fuel bed. Though the function can be defined to reflect varying fuel loads and distributions of burning, the results presented are based on sectionally uniform heating rates.

The formulation of the boundary value problem is unique in that analytic jump conditions are derived for the fire-column boundary. Such a formulation obviates the need for extensive far-field calculations and allows demonstration of the dependence of induced fire winds on the fire area and heat release rate. Improvements to the model could include the use of multiparameter models to describe the structure of local turbulence and hot-gas/smoke radiation (in place of the simple one-parameter formulations used here) as well as a heat release function dependent on the local thermodynamic and flow conditions.

The effects of the model parameters were explored in a sensitivity study. Varying fire areas, heat distributions and release rates, mixing coefficients, and radiation lengths were investigated. Qualitatively similar flows were observed for all parameter ranges, despite significant quantitative differences. The fire-induced velocities increased with both heat release and fire area. For small values, the

velocity increased almost linearly. For larger values of either fire area or heat release rate, the induced velocities increased more slowly. Presumably, the magnitudes are limited by compressibility effects through a slowing production of buoyancy.

Variations in the degree of turbulent mixing produced substantial changes in the velocity fields. As expected, large mixing coefficients tend to reduce the velocities at the fire periphery; smaller values produce higher velocities. In general, the mixing coefficients should reflect both the apparent surface roughness (urban structure) and the fire-generated turbulence. The present analysis used constant eddy diffusivities.

Fuel distributions and heat release rates were developed to explore the effects of varying city constructions and fuel densities on the fire environment in three model urban areas. Though the models provide only a simple representation of a city cross section, the results indicate the importance of modeling a particular fuel bed. More refined distributions based on city surveys could be used.

A fire radius of 12 km is assumed for each model urban area, since megaton-yield explosions would cause area fires of that magnitude. Each model area is characterized by a high-density city center, a lower density annulus representing a mixed residential/industrial construction, and an outer belt of low-density residential tracts. The heat release function reflected the sectionally variable fuel densities and loadings.

Computed results for each fire illustrate the dependence of the fire winds and temperature levels on the urban geography. The most severe fires occur in the higher density cities, though even the lower density constructions support high temperatures and velocities. Application of those results to definition of shelter hardness (thermal) would imply different criteria for each city.

An additional set of numerical experiments considered each model area with a reduced level of burning in the center region. A slow-burning debris field created by extensive blast damage may foster such a heat release distribution. In general, peak velocities were only

slightly reduced, though temperature changes were substantial. Temperature levels in the central region were markedly reduced from those in the full-burning outer annulus. It is reasonable to expect that the fire winds would fan the slow-burning central area, creating a more severe environment.

The analysis and results presented here describe the environment of a large area fire at fixed times. Past experience indicates that such fires develop, peak, and ebb over a period of several hours. The methods developed here can be used successively to estimate the environment at different times in the fire evolution. The high velocities and temperatures predicted would encourage a rapid internal fire spread, which may considerably hasten burnout of the city. Improved estimates would result from use of a responsive heat release function that depends on the local gas dynamic state. A time-dependent calculation that includes the high-resolution analysis presented here could provide a complete map of the evolution and ebb of urban fires. Synthesis of the present analysis with a large hydro-code may provide a numerically efficient model for calculating the mesoscale flow field of a large area fire.

Appendix

PREDICTION-ALGORITHM DOCUMENTATION

This appendix documents the computer algorithm used to generate the predictions and other results presented in Secs. II through IV. The algorithm yields numerical solutions to the turning-region boundary value problem derived in Part I.

The turning-region problem is defined by the following balances:

$$\frac{\partial}{\partial r} (r\rho u) + \frac{\partial}{\partial y} (r\rho v) = 0 ,$$

$$\rho \left(u \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial P}{\partial r} + M_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) - \frac{u}{r^2} \right) ,$$

$$\frac{\partial P}{\partial y} + A\rho = 0 ,$$

$$\rho \left(u \frac{\partial T}{\partial r} + v \frac{\partial T}{\partial y} \right) = q(r, y) - \sigma(T^4 - 1) + K_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right) ,$$

$$\rho T = 1 , \tag{A.1}$$

subject to

$$v = 0 \quad \text{on } y = 0 , \tag{A.2a}$$

$$u = \frac{\partial T}{\partial r} = 0 \quad \text{on } r = 0 , \tag{A.2b}$$

$$P + Ay_{\max} = 0 \quad \text{on } y = y_{\max} , \tag{A.2c}$$

$$M_1 \frac{\partial u}{\partial r} = \left(\frac{u}{T} \right)^2 (T - 1) + (P + Ay) , \quad K_1 \frac{\partial T}{\partial r} = \frac{u}{T} (T - 1) \\ \text{on } r = 1 . \tag{A.2d}$$

The flow chart in Fig. A.1 summarizes the solution algorithm. As indicated in the figure (and discussed in Part I, pp. 16-17), the algorithm uses an iterative "shooting" method [Keller, 1968] to solve the overall boundary value problem. Each shoot employs a nonlinear Crank-Nicolson finite difference scheme.

INPUTS AND OUTPUTS

The following is an ordered list of the FORTRAN inputs required for automated algorithm usage:

a. System parameters:

A	A
SIGMA	σ
XNUIN	M_1
XKIN	K_1

b. Mesh descriptors:

YMAX	y_{\max}
M	Number of finite difference cells in the radial direction. [†]
N	Number of finite difference cells in the vertical direction. [†]

c. Iteration parameters:

ETLINE	Maximum absolute error allowed in solving discretized Crank-Nicolson equations on any line of constant y .
ETOLP	Maximum absolute error allowed in P on $y = y_{\max}$.
MAXITL	Maximum number of Newton iterations allowed in solving discretized equations on any line of constant y .
MAXITP	Maximum number of complete-shoot iterations allowed in solving the complete boundary value problem.

[†] In the present coding, cell widths are taken to be uniform, the common width being denoted by Δr . For $0 \leq y \leq 5$, cell heights Δy are also taken to be Δr ; for $5 \leq y \leq y_{\max}$, they are taken to be $2 \Delta r$.

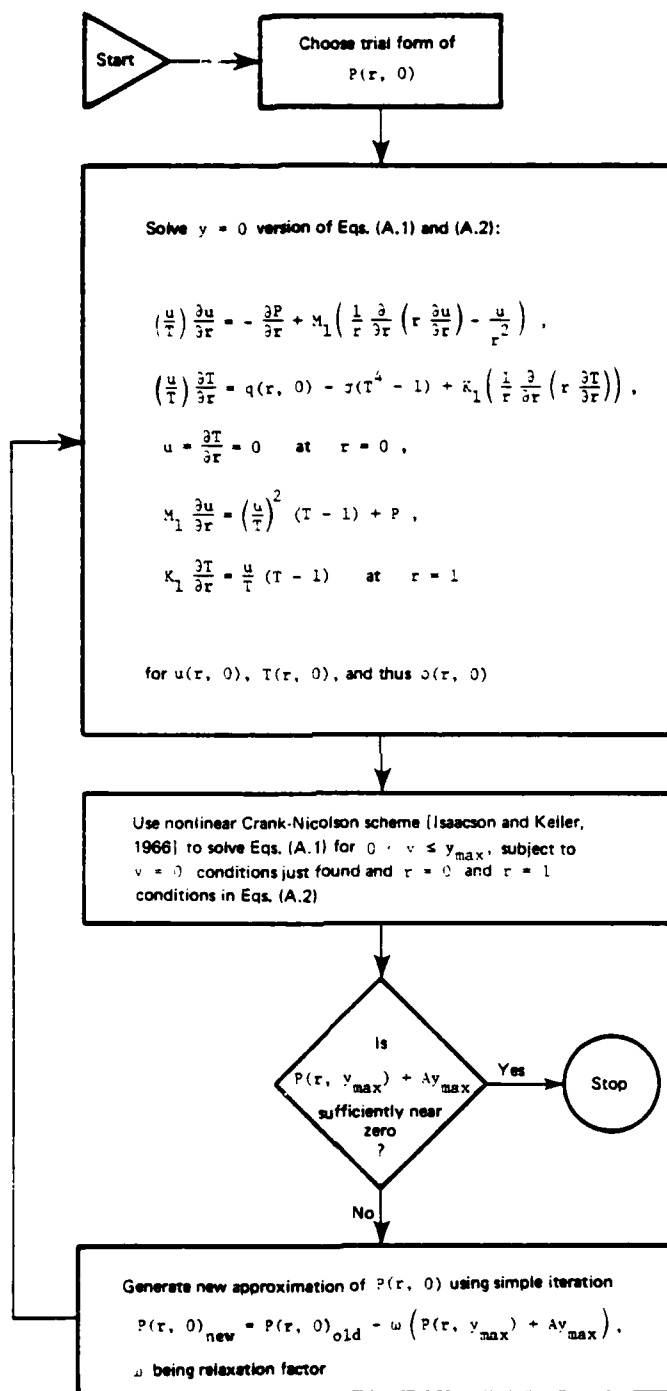


Fig. A.1--Flow chart of prediction algorithm for turning-region boundary value problem

d. Program control parameters:

ALPHA $(Qq)_{\max}$, maximum value of Qq in present coding.
 BETA, BLOSS Parameters available for either system description or program control. (These parameters are currently unused, so they are set equal to zero.)
 IGUESS Parameter that controls the initial choices of first-shoot values along $y = 0$.
 IGUESS = 1: Discretized versions of $P(r, 0)$, $T(r, 0)$, and $u(r, 0)$ must be supplied as inputs.
 IGUESS = 2: "Standard" initial choices are made automatically.
 IGUESS = 3: Discretized versions of $P(r, 0)$, $T(r, 0)$, and $u(r, 0)$ from the last algorithm run are used automatically.

The "standard" initial guesses in the present coding represent the ground-level pressure, temperature, and radial velocity profiles predicted in Part I (pp. 13-16) for the case of a weakly heated flow:

$$\begin{aligned} P(r, 0) &= - (Qq)_{\max} \left(\frac{A}{4\sigma} \right) , \\ T(r, 0) &= 1.0 + (Qq)_{\max} \left(\frac{1}{4\sigma} \right) , \\ u(r, 0) &= - (Qq)_{\max} \left(\frac{A}{4\sigma M_1} \right) r . \end{aligned} \tag{A.3}$$

Finally, the functional form of $q(r, y)$ must be prescribed. Currently, it is given in the form used in our analysis:

$$q(r, y) = \begin{cases} (Qq)_{\max} & \text{for } 0 \leq y \leq 0.25 \\ (Qq)_{\max} \left(\frac{4}{3} (1 - y) \right) & \text{for } 0.25 \leq y \leq 1.0 \\ 0 & \text{for } y \geq 1.0 \end{cases} \quad . \quad (A.4)$$

Changes require reprogramming in subroutine BCFUNC. As a user option, the dissipation coefficients M_1 and K_1 may also be made to depend on r and y through reprogramming, also in BCFUNC. Currently, those coefficients are simply taken as constants.

A sample input data stream is

A = 0.217 , SIGMA = 0.110 , XNUIN = XKIN = 0.200 ;

YMAX = 10 , M = 40 , N = 300 ;

ETLINE = 0.0003 , ETOLP = 0.001 , MAXITL = 30 , MAXITP = 9 ;

ALPHA = 1.6 , BETA = 0.0 , BLOSS = 0.0 , IGUESS = 3 . (A.5)

The corresponding output is listed in Table A.1. All output data are automatically dumped onto a disk file and used in constructing the vector, contour, and profile plots presented in Secs. II through IV.

PROGRAM .LOW

Figure A.1 outlines the overall flow of the computer algorithm. Inputs, outputs, and the basic shooting iteration are controlled by the main program. Figure A.2 presents a flow chart of that program. In subroutine BCFUNC, functional forms that may be varied [e.g., $q(r, y)$] are specified; and in subroutine SPRINT, final output data are printed. Subroutine MSWEEP performs most of the computations--i.e., those providing a one-shoot finite difference solution to Eqs. (A.1) for given data along $y = 0$, $r = 0$, and $r = 1$. The flow of that subroutine is shown in Figs. A.4 and A.5 below (pp. 80-81); the underlying numerical analysis is detailed in the accompanying

Table A.1

SAMPLE CODE OUTPUT

FIRES: SOLUTION OF COMBUSTION LAYER BOUNDARY VALUE PROBLEM

SYSTEM PARAMETERS: A = 0.217 SIGMA = 0.110 NH = 0.200 K = 0.200

WEND: M = 40 NR = 0.025 N = 300 DY = 0.025

ITERATION PARAMETERS: FTIME = 0.000100 MAXITL = 50 FIDLP = 0.10000 MAXITP = 9

INITIAL PARAMETERS: ALPHA = 1.000 BETA = 0.000 MUOSS = 0.000

FOR J = 1 (Y = 0.000):

I	R	U	V	T	RHO	P	PR	MU-IRR	K-IRR	Q(T)
1	0.000	0.000	0.000	1.930	0.516	-0.103	0.000	0.000	0.000	0.150
2	0.000	-0.019	0.000	1.930	0.516	-0.103	0.000	0.000	0.000	0.150
3	0.000	-0.039	0.000	1.930	0.516	-0.103	0.000	0.000	0.000	0.150
4	0.000	-0.057	0.000	1.930	0.516	-0.103	0.000	0.000	-0.320	0.150
5	0.000	-0.074	0.000	1.930	0.516	-0.103	0.000	0.000	0.000	0.161
6	0.000	-0.089	0.000	1.930	0.517	-0.102	0.000	0.000	-0.320	0.165
7	0.000	-0.113	0.000	1.934	0.517	-0.102	0.000	0.000	-0.320	0.171
8	0.000	-0.132	0.000	1.931	0.517	-0.101	0.000	0.000	-0.320	0.174
9	0.000	-0.150	0.000	1.931	0.516	-0.100	0.000	0.000	-0.320	0.174
10	0.000	-0.168	0.000	1.926	0.516	-0.100	0.000	0.000	-0.320	0.181
11	0.000	-0.186	0.000	1.926	0.519	-0.100	0.000	0.000	-0.320	0.180
12	0.000	-0.204	0.000	1.925	0.520	-0.100	0.000	0.000	-0.320	0.186
13	0.000	-0.221	0.000	1.920	0.521	-0.100	0.000	0.000	-0.320	0.206
14	0.000	-0.238	0.000	1.916	0.522	-0.100	0.000	0.000	-0.320	0.215
15	0.000	-0.255	0.000	1.913	0.523	-0.100	0.000	0.000	-0.320	0.215
16	0.000	-0.272	0.000	1.908	0.524	-0.100	0.000	0.000	-0.320	0.237
17	0.000	-0.288	0.000	1.900	0.525	-0.100	0.000	0.000	-0.320	0.242
18	0.000	-0.304	0.000	1.899	0.527	-0.100	0.000	0.000	-0.320	0.264
19	0.000	-0.319	0.000	1.893	0.528	-0.100	0.000	0.000	-0.320	0.279
20	0.000	-0.334	0.000	1.887	0.530	-0.100	0.000	0.000	-0.320	0.297
21	0.000	-0.349	0.000	1.880	0.532	-0.100	0.000	0.000	-0.320	0.315
22	0.000	-0.365	0.000	1.873	0.534	-0.100	0.000	0.000	-0.320	0.336
23	0.000	-0.377	0.000	1.866	0.536	-0.100	0.000	0.000	-0.320	0.376
24	0.000	-0.390	0.000	1.857	0.539	-0.100	0.000	0.000	-0.320	0.402
25	0.000	-0.404	0.000	1.848	0.541	-0.100	0.000	0.000	-0.320	0.427
26	0.000	-0.416	0.000	1.839	0.544	-0.100	0.000	0.000	-0.320	0.452
27	0.000	-0.428	0.000	1.828	0.547	-0.100	0.000	0.000	-0.320	0.482
28	0.000	-0.440	0.000	1.817	0.550	-0.100	0.000	0.000	-0.320	0.511
29	0.000	-0.452	0.000	1.805	0.554	-0.100	0.000	0.000	-0.320	0.542
30	0.000	-0.462	0.000	1.792	0.558	-0.100	0.000	0.000	-0.320	0.576
31	0.000	-0.471	0.000	1.779	0.562	-0.100	0.000	0.000	-0.320	0.600
32	0.000	-0.483	0.000	1.764	0.567	-0.100	0.000	0.000	-0.320	0.645
33	0.000	-0.493	0.000	1.748	0.572	-0.100	0.000	0.000	-0.320	0.683
34	0.000	-0.502	0.000	1.732	0.577	-0.100	0.000	0.000	-0.320	0.720
35	0.000	-0.510	0.000	1.714	0.583	-0.100	0.000	0.000	-0.320	0.761
36	0.000	-0.519	0.000	1.695	0.590	-0.100	0.000	0.000	-0.320	0.802
37	0.000	-0.527	0.000	1.675	0.597	-0.100	0.000	0.000	-0.320	0.844
38	0.000	-0.534	0.000	1.653	0.605	-0.100	0.000	0.000	-0.320	0.889
39	0.000	-0.541	0.000	1.630	0.613	-0.100	0.000	0.000	-0.320	0.933
40	0.000	-0.548	0.000	1.606	0.623	-0.100	0.000	0.000	-0.320	0.976
41	0.000	-0.554	0.000	1.581	0.633	-0.100	0.000	0.000	-0.320	1.023

Table A.1--Continued

FOR J = 2 (V = 0.025):											
I	R	II	V	T	RHO	P	PR	MIARR	KSTR	Q(T)	
1	0.000	0.000	0.036	1.941	0.515	-0.180	0.000	0.000	0.000	0.154	
2	0.025	-0.017	0.036	1.941	0.515	-0.180	0.000	0.014	-0.049	0.154	
3	0.050	-0.033	0.036	1.940	0.516	-0.180	0.000	0.014	-0.079	0.155	
4	0.075	-0.050	0.036	1.940	0.516	-0.180	0.020	0.045	-0.078	0.156	
5	0.100	-0.067	0.035	1.939	0.516	-0.179	0.020	0.041	-0.078	0.159	
6	0.125	-0.083	0.035	1.938	0.516	-0.179	0.000	0.015	-0.080	0.162	
7	0.150	-0.099	0.035	1.936	0.516	-0.179	0.020	0.045	-0.082	0.167	
8	0.175	-0.116	0.035	1.935	0.517	-0.178	0.040	0.069	-0.085	0.172	
9	0.200	-0.131	0.035	1.933	0.517	-0.177	0.040	0.067	-0.089	0.178	
10	0.225	-0.147	0.035	1.931	0.518	-0.176	0.040	0.063	-0.092	0.185	
11	0.250	-0.163	0.034	1.929	0.519	-0.175	0.020	0.046	-0.096	0.192	
12	0.275	-0.178	0.034	1.926	0.519	-0.175	0.040	0.070	-0.101	0.201	
13	0.300	-0.194	0.034	1.923	0.520	-0.174	0.040	0.092	-0.106	0.211	
14	0.325	-0.209	0.034	1.920	0.521	-0.172	0.040	0.090	-0.112	0.221	
15	0.350	-0.224	0.033	1.916	0.522	-0.171	0.040	0.067	-0.119	0.233	
16	0.375	-0.238	0.033	1.912	0.523	-0.170	0.040	0.060	-0.125	0.246	
17	0.400	-0.252	0.033	1.907	0.524	-0.169	0.040	0.091	-0.133	0.260	
18	0.425	-0.266	0.032	1.903	0.526	-0.167	0.040	0.089	-0.141	0.275	
19	0.450	-0.280	0.032	1.897	0.527	-0.166	0.040	0.109	-0.150	0.291	
20	0.475	-0.293	0.032	1.892	0.529	-0.164	0.040	0.086	-0.159	0.309	
21	0.500	-0.306	0.031	1.885	0.530	-0.162	0.040	0.086	-0.170	0.327	
22	0.525	-0.319	0.031	1.879	0.532	-0.161	0.040	0.106	-0.180	0.346	
23	0.550	-0.332	0.031	1.871	0.534	-0.159	0.079	0.104	-0.204	0.393	
24	0.575	-0.346	0.030	1.863	0.537	-0.157	0.079	0.102	-0.216	0.417	
25	0.600	-0.359	0.030	1.855	0.539	-0.156	0.079	0.100	-0.229	0.443	
26	0.625	-0.372	0.029	1.845	0.542	-0.154	0.079	0.099	-0.243	0.471	
27	0.650	-0.385	0.029	1.835	0.545	-0.152	0.079	0.099	-0.258	0.501	
28	0.675	-0.398	0.029	1.825	0.548	-0.150	0.079	0.097	-0.273	0.531	
29	0.700	-0.410	0.029	1.813	0.552	-0.148	0.079	0.095	-0.287	0.564	
30	0.725	-0.421	0.029	1.801	0.555	-0.146	0.079	0.094	-0.305	0.598	
31	0.750	-0.431	0.028	1.787	0.559	-0.144	0.079	0.092	-0.320	0.634	
32	0.775	-0.441	0.028	1.773	0.564	-0.142	0.099	0.111	-0.337	0.671	
33	0.800	-0.449	0.028	1.758	0.569	-0.139	0.099	0.108	-0.353	0.709	
34	0.825	-0.456	0.028	1.742	0.574	-0.137	0.079	0.085	-0.370	0.749	
35	0.850	-0.463	0.028	1.724	0.580	-0.135	0.079	0.104	-0.386	0.791	
36	0.875	-0.467	0.028	1.706	0.586	-0.132	0.098	0.122	-0.402	0.833	
37	0.900	-0.475	0.028	1.686	0.594	-0.129	0.098	0.098	-0.417	0.877	
38	0.925	-0.480	0.028	1.665	0.601	-0.127	0.098	0.095	-0.431	0.921	
39	0.950	-0.489	0.028	1.643	0.609	-0.124	0.118	0.113	-0.445	0.966	
40	0.975	-0.497	0.028	1.619	0.614	-0.121	0.118	0.109	-0.445	1.012	
41	1.000	-0.504	0.028	1.594	0.627	-0.118	0.118	0.109	-0.445	1.012	

Table A.1--Continued

FOR J = 101 (V = 10.000):

I	R	U	V	Y	RHO	P	PR	MUHR	KATR	Q(1)
1	0.000	0.000	4.035	1.000	0.992	0.000	0.000	0.000	0.000	-0.003
2	0.025	-0.002	4.034	1.000	0.992	0.000	-0.003	-0.002	0.000	-0.003
3	0.050	-0.005	4.033	1.000	0.992	0.000	-0.007	-0.005	-0.001	-0.003
4	0.075	-0.007	4.015	1.000	0.992	0.000	0.000	0.017	-0.002	-0.003
5	0.100	-0.010	4.785	1.000	0.992	0.001	0.005	0.012	-0.002	-0.003
6	0.125	-0.012	4.771	1.000	0.992	0.000	-0.019	0.013	-0.001	-0.003
7	0.150	-0.014	4.754	1.000	0.992	0.000	-0.003	0.010	-0.002	-0.003
8	0.175	-0.017	4.712	1.000	0.993	0.000	0.013	0.020	-0.001	-0.003
9	0.200	-0.019	4.657	1.000	0.993	0.001	0.010	0.024	-0.002	-0.003
10	0.225	-0.021	4.617	1.007	0.993	0.001	-0.014	0.000	-0.001	-0.003
11	0.250	-0.023	4.508	1.007	0.993	0.000	-0.017	0.001	-0.001	-0.003
12	0.275	-0.025	4.547	1.007	0.993	0.000	-0.001	0.019	-0.001	-0.003
13	0.300	-0.026	4.403	1.007	0.993	0.000	0.016	0.037	-0.001	-0.003
14	0.325	-0.030	4.303	1.007	0.993	0.001	0.013	0.033	-0.001	-0.003
15	0.350	-0.031	4.140	1.007	0.993	0.000	-0.010	0.010	-0.001	-0.003
16	0.375	-0.033	4.200	1.007	0.993	0.000	-0.013	0.009	-0.001	-0.003
17	0.400	-0.035	4.226	1.007	0.993	0.000	0.004	0.024	-0.001	-0.003
18	0.425	-0.037	4.153	1.007	0.993	0.000	0.001	0.025	-0.001	-0.003
19	0.450	-0.039	4.080	1.007	0.993	0.000	-0.002	0.023	0.000	-0.003
20	0.475	-0.040	3.997	1.007	0.993	0.000	-0.016	0.041	0.000	-0.003
21	0.500	-0.042	3.916	1.007	0.993	0.001	-0.007	0.018	-0.001	-0.003
22	0.525	-0.043	3.848	1.007	0.993	0.000	-0.009	0.016	0.000	-0.003
23	0.550	-0.044	3.770	1.007	0.993	0.000	0.000	0.035	0.000	-0.003
24	0.575	-0.046	3.683	1.007	0.993	0.000	0.006	0.032	0.000	-0.003
25	0.600	-0.047	3.597	1.007	0.993	0.000	0.004	0.029	0.000	-0.003
26	0.625	-0.049	3.515	1.007	0.994	0.000	-0.002	0.027	0.000	-0.003
27	0.650	-0.049	3.435	1.006	0.994	0.000	-0.001	0.024	0.001	-0.003
28	0.675	-0.050	3.357	1.006	0.994	0.000	-0.003	0.022	0.000	-0.003
29	0.700	-0.051	3.283	1.006	0.994	0.000	-0.005	0.020	0.001	-0.003
30	0.725	-0.051	3.212	1.006	0.994	0.000	-0.007	0.018	0.000	-0.003
31	0.750	-0.052	3.145	1.006	0.994	0.000	-0.010	0.015	0.001	-0.003
32	0.775	-0.053	3.069	1.006	0.994	0.000	0.008	0.033	0.000	-0.003
33	0.800	-0.054	2.985	1.006	0.994	0.000	0.005	0.030	0.001	-0.003
34	0.825	-0.054	2.917	1.006	0.994	0.000	-0.017	0.006	0.001	-0.003
35	0.850	-0.054	2.854	1.006	0.994	-0.001	0.000	0.024	0.001	-0.003
36	0.875	-0.055	2.772	1.006	0.994	0.000	0.017	0.041	0.001	-0.003
37	0.900	-0.055	2.694	1.006	0.994	0.000	-0.006	0.016	0.000	-0.003
38	0.925	-0.055	2.636	1.006	0.994	0.000	-0.009	0.013	0.002	-0.003
39	0.950	-0.055	2.571	1.006	0.994	0.000	0.007	0.029	0.001	-0.003
40	0.975	-0.055	2.500	1.006	0.994	0.000	0.003	0.075	0.000	-0.003
41	1.000	-0.055	2.436	1.006	0.994	0.000	0.001	0.025	0.000	-0.003

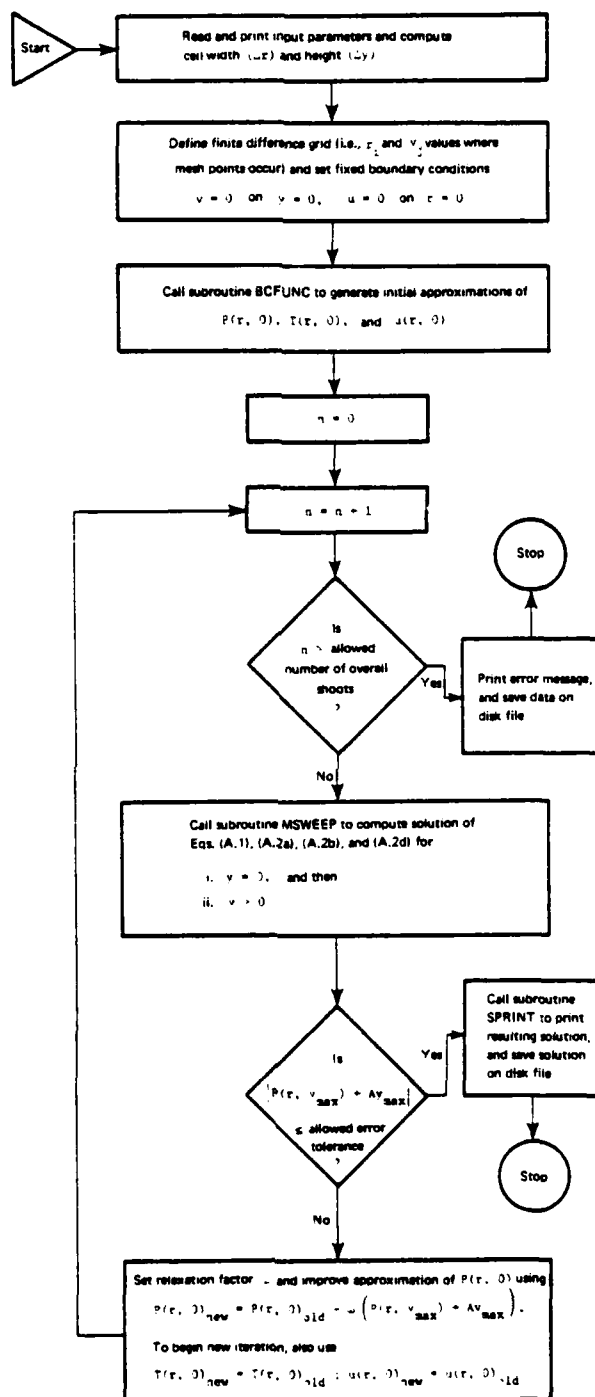


Fig. A.2--Flow chart of main program

text. Complete FORTRAN listings of the main program and all sub-routines are presented at the end of this appendix.

FINITE DIFFERENCE ALGORITHM AND SUBROUTINE MSWEEP

The finite difference scheme underlying the computer algorithm is based on the rectangular grid and "stencils" in Fig. A.3. The grid has uniform cell widths ($\Delta r = 1/M$) and piecewise uniform heights ($\Delta y = \Delta r$ for $0 \leq y \leq 5$, $y = 2 \Delta r$ for $y > 5$). Mesh points are thus located at (r_i, y_j) points with

$$\begin{aligned} r_i &= (i - 1) \Delta r, & 1 \leq i \leq M + 1, \\ y_j &= \begin{cases} (j - 1) \Delta r, & 1 \leq j \leq 5M + 1 \\ 5 + (j - 5M - 1)(2 \Delta r), & 5M + 2 \leq j \leq N + 1 \end{cases} \end{aligned} \quad (A.6)$$

Dependent variables evaluated at those points are given corresponding (i, j) suffices. For example, $r_1 = 0$ (and not Δr), $y_{N+1} = y_{\max}$, and $u_{1,N+1} = u(0, y_{\max})$. The accurate approximation of $\{u_{i,j}, v_{i,j}, P_{i,j}, T_{i,j}, \rho_{i,j}\}_{1 \leq i \leq M+1, 1 \leq j \leq N+1}$ constitutes a numerical solution of the problem posed by Eqs. (A.1) and (A.2). The stencils in Fig. A.3, explained below (pp. 82-83), indicate the types of differencing used in the algorithm.

Along the $y = 0$ line (where $j = 1$), $v \equiv 0$. As shown in Fig. A.2, a guess at P along that line [actually, the $\{P_{i1}\}_{i=1}^{M+1}$ values] is also made before the MSWEEP subroutine is called. As indicated in the first large block of Fig. A.1, Eqs. (A.1) and (A.2) then reduce along the $y = 0$ line to the following ordinary-differential-equation boundary value problem for u and T alone (with $\rho = 1/T$):

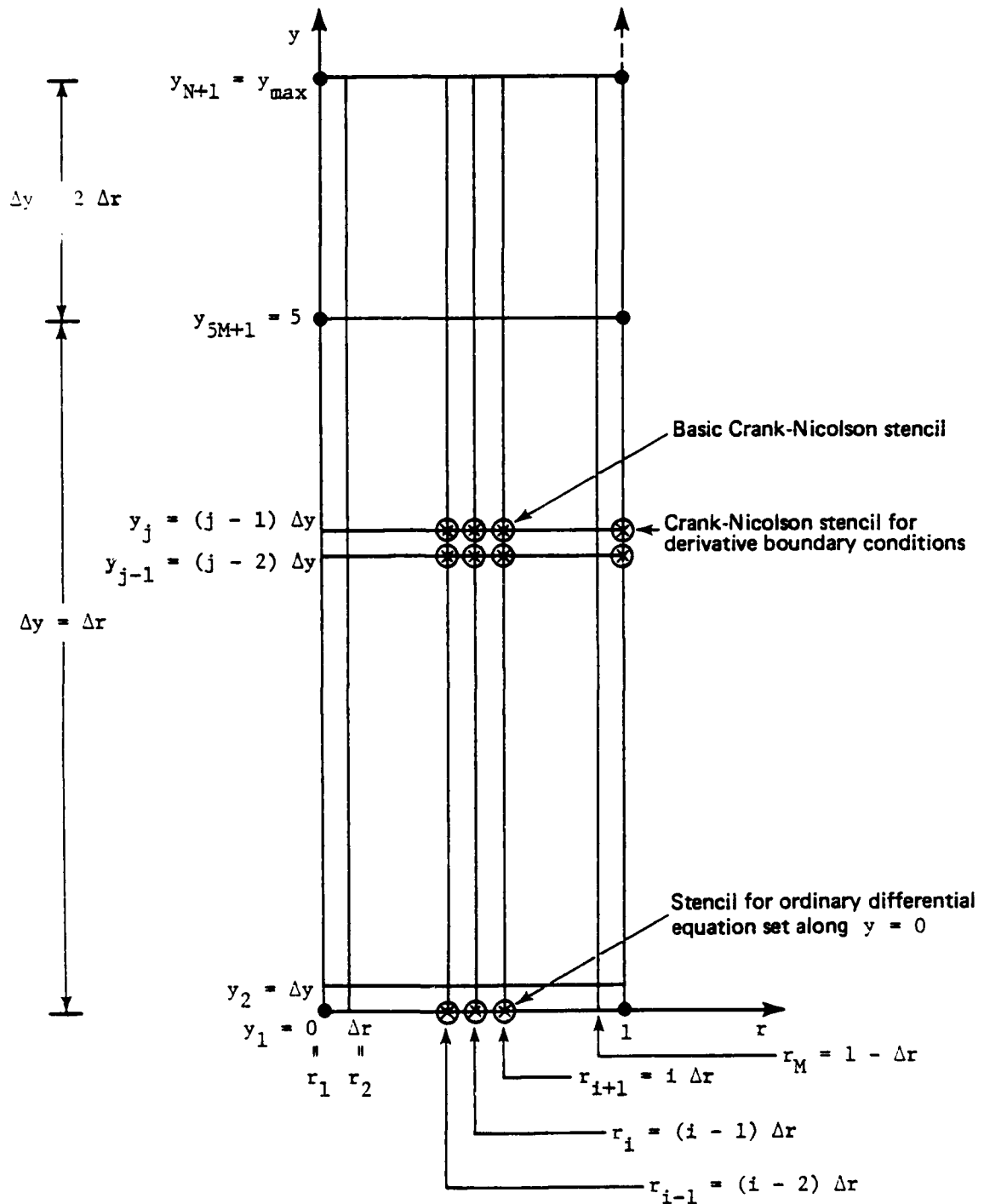


Fig. A.3--Finite difference grid and stencils for numerical solution of turning-region problem

$$\left(\frac{u}{T}\right) \frac{\partial u}{\partial r} = -\frac{\partial P}{\partial r} + M_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) - \frac{u}{r^2} \right),$$

$$\left(\frac{u}{T}\right) \frac{\partial T}{\partial r} = q(r, 0) - \sigma(T^4 - 1) + K_1 \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \right),$$

$$u = \frac{\partial T}{\partial r} = 0 \quad \text{at } r = 0,$$

$$M_1 \frac{\partial u}{\partial r} = \left(\frac{u}{T}\right)^2 (T - 1) + P, \quad K_1 \frac{\partial T}{\partial r} = \frac{u}{T} (T - 1)$$

$$\text{at } r = 1. \quad (\text{A.7})$$

The standard finite-difference solution for this problem involves the solution of

$$\vec{F}(\vec{x}) = \vec{0}, \quad (\text{A.8})$$

where

$$\vec{x} \equiv \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \\ \tilde{x}_4 \\ \vdots \\ \vdots \\ \tilde{x}_{2M-3} \\ \tilde{x}_{2M-2} \\ \tilde{x}_{2M-1} \\ \tilde{x}_{2M} \end{bmatrix} = \begin{bmatrix} u_{2,1} \\ T_{2,1} \\ u_{3,1} \\ T_{3,1} \\ \vdots \\ \vdots \\ u_{M,1} \\ T_{M,1} \\ u_{M+1,1} \\ T_{M+1,1} \end{bmatrix} \quad (\text{A.9})$$

and the components of \vec{F} are the finite difference equations obtained from the discretization of Eqs. (A.7). The Crank-Nicolson solution of Eqs. (A.1)--subject to Eqs. (A.2b) and (A.2d), and the solution of Eqs. (A.7) [with $P(r, 0)$ given]--also involves the solution of Eq. (A.8) for successive j , $j = 2, 3, 4, \dots, N, N + 1$. In that case, the components of \vec{F} are slightly different from those for $j = 1$. For each fixed $j (\geq 2)$, \vec{x} is redefined [cf. Eq. (A.9)] as

$$\vec{x} \equiv \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \\ \tilde{x}_4 \\ \vdots \\ \vdots \\ \tilde{x}_{2M-3} \\ \tilde{x}_{2M-2} \\ \tilde{x}_{2M-1} \\ \tilde{x}_{2M} \end{bmatrix} = \begin{bmatrix} u_{2,j} \\ T_{2,j} \\ u_{3,j} \\ T_{3,j} \\ \vdots \\ \vdots \\ u_{M,j} \\ T_{M,j} \\ u_{M+1,j} \\ T_{M+1,j} \end{bmatrix} \quad (A.10)$$

The overall flow in subroutine MSWEEP is thus as outlined in Fig. A.4, Newton's method (see Fig. A.5) being used in all cases to solve the component equations of Eq. (A.8) because they are nonlinear.

To fully describe subroutine MSWEEP, we must define the following processes:

1. The specific finite-difference schemes used to reduce Eqs. (A.7) to Eq. (A.8) for $j = 1$ ($y = 0$), and Eqs. (A.1), (A.2b), and (A.2d) to Eq. (A.8) for $j \geq 2$ ($y > 0$).
2. The corresponding specifications of J (as $\partial \vec{F} / \partial \vec{x}$; see Fig. A.5).
3. The specific Gaussian elimination scheme used to compute $\vec{\delta}$ (as $-J^{-1} \vec{F}$; see Fig. A.5).

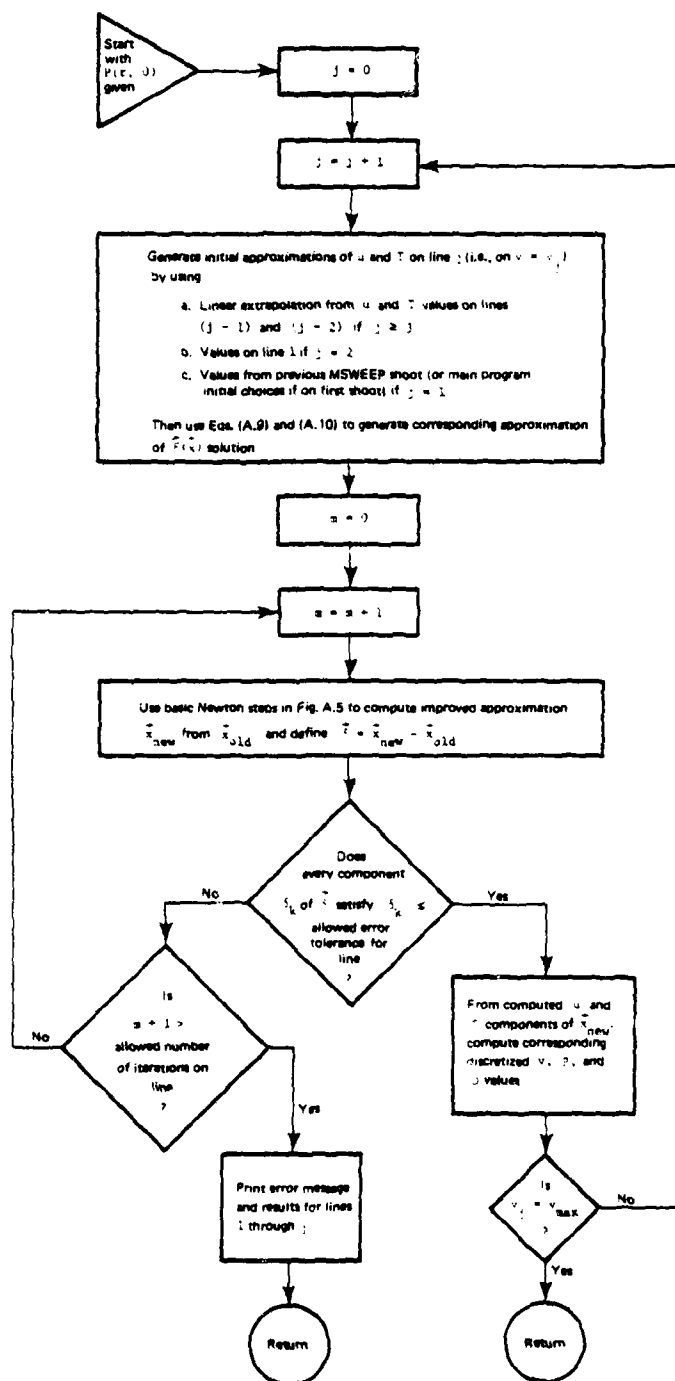


Fig. A.4--Flow chart of subroutine MSWEEP

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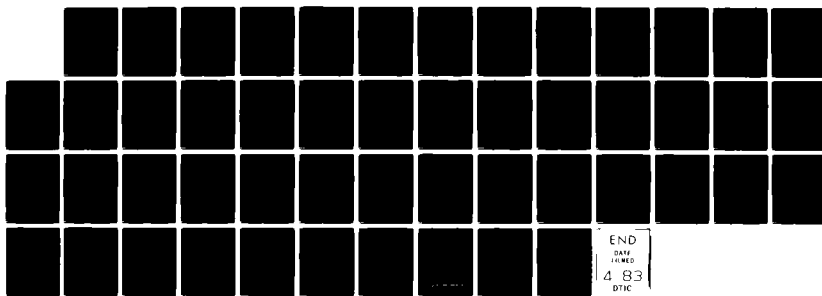
ANALYSIS OF THE LARGE URBAN FIRE ENVIRONMENT PART 11
PARAMETRIC ANALYSIS A. (U) PACIFIC-SIERRA RESEARCH CORP
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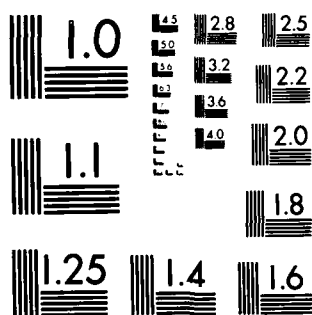
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M-2



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

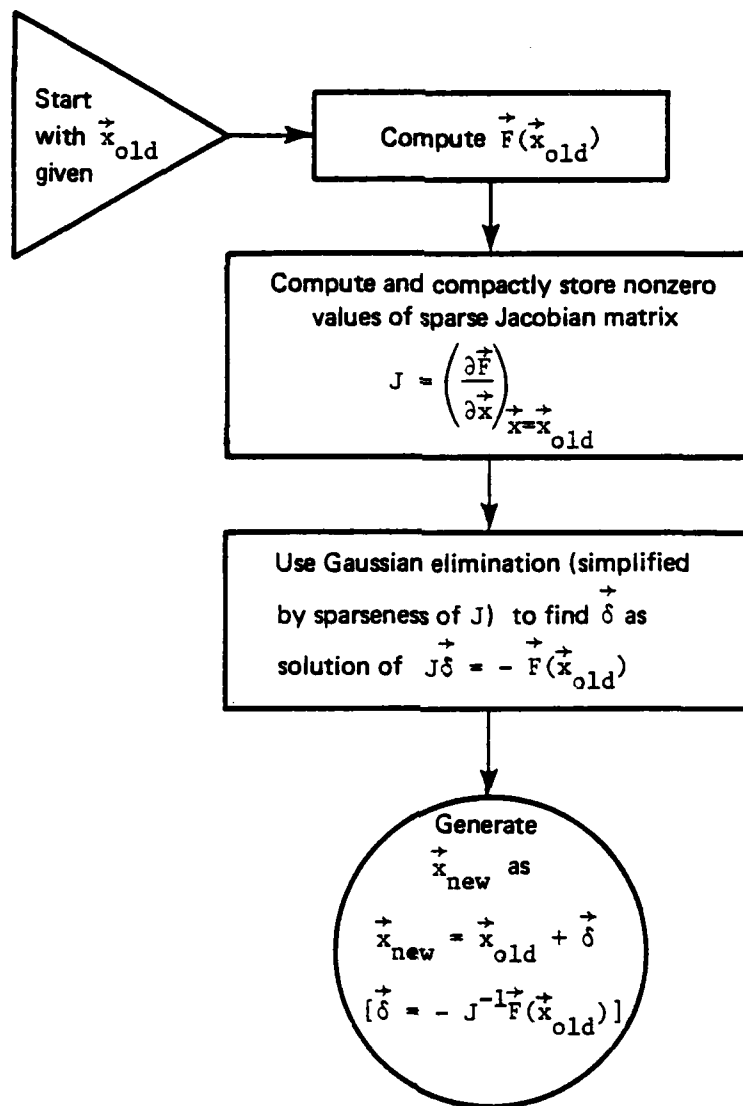


Fig. A.5--Flow chart of Newton steps used in subroutine MSWEEP

For $j = 1$, the usual discretization for second-order ordinary differential equations is used to reduce Eqs. (A.7) to Eq. (A.8). That is, for any dependent variable w , interior derivatives are replaced by the centered difference approximations

$$\begin{aligned} \left(\frac{\partial^2 w}{\partial r^2} \right)_{i,1} &\rightarrow \frac{w_{i+1,1} - 2w_{i,1} + w_{i-1,1}}{(\Delta r)^2}, \\ \left(\frac{\partial w}{\partial r} \right)_{i,1} &\rightarrow \frac{w_{i+1,1} - w_{i-1,1}}{2 \Delta r}. \end{aligned} \quad (A.11)$$

In addition, boundary derivatives are taken as, for example,

$$\left(\frac{\partial w}{\partial r} \right)_{1,1} \rightarrow \frac{w_{2,1} - w_{1,1}}{\Delta r}. \quad (A.12)$$

Thus, as indicated by the corresponding discretization stencil at the bottom of Fig. A.3, no more than three values of u and T are involved in each component equation in Eq. (A.8) [see Eq. (A.9)]--and those values are at successive r_i . For each $j \geq 2$, the Crank-Nicolson scheme to be defined by Eqs. (A.13) and (A.14) is used to reduce Eqs. (A.1), (A.2b), and (A.2d) to Eq. (A.8). Centered differences are also used, with interior and boundary approximation stencils as shown in Fig. A.3, interior approximations being

$$\begin{aligned} \left(\frac{\partial^2 w}{\partial r^2} \right)_{i,j} &\rightarrow \frac{1}{2} \left(\frac{w_{i+1,j} - 2w_{i,j} + w_{i-1,j}}{(\Delta r)^2} + \frac{w_{i+1,j-1} - 2w_{i,j-1} + w_{i-1,j-1}}{(\Delta r)^2} \right), \\ \left(\frac{\partial w}{\partial r} \right)_{i,j} &\rightarrow \frac{1}{2} \left(\frac{w_{i+1,j} - w_{i-1,j}}{2 \Delta r} + \frac{w_{i+1,j-1} - w_{i-1,j-1}}{2 \Delta r} \right), \end{aligned}$$

$$\left(\frac{\partial w}{\partial y}\right)_{i,j} \rightarrow \left(\frac{w_{i,j} - w_{i,j-1}}{\Delta y}\right),$$

$$(w)_{i,j} \rightarrow \frac{1}{2} (w_{i,j} + w_{i,j-1}), \quad (\text{A.13})$$

and the boundary formulas being of the form

$$\left(\frac{\partial w}{\partial r}\right)_{1,j} \rightarrow \frac{1}{2} \left(\frac{w_{2,j} - w_{1,j}}{\Delta r} + \frac{w_{2,j-1} - w_{1,j-1}}{\Delta r} \right),$$

$$(w)_{1,j} \rightarrow \frac{1}{2} (w_{1,j} + w_{1,j-1}). \quad (\text{A.14})$$

As in linear problems [Isaacson and Keller, 1966], the resulting nonlinear scheme has proven to be convergent, stable, and accurate in providing solutions to the turning-region boundary value problem.

In reducing either Eqs. (A.7) or Eqs. (A.1), (A.2b), and (A.2d) to Eq. (A.8) by means of Eqs. (A.11) through (A.14), it proves convenient--both notationally and computationally--to begin by decomposing \vec{x} (for all j) into

$$\vec{u} = \begin{bmatrix} u_{2,j} \\ u_{3,j} \\ \vdots \\ u_{M,j} \\ u_{M+1,j} \end{bmatrix} \quad \text{and} \quad \vec{T} = \begin{bmatrix} T_{2,j} \\ T_{3,j} \\ \vdots \\ T_{M,j} \\ T_{M+1,j} \end{bmatrix}, \quad (\text{A.15})$$

and arranging the corresponding $\vec{F}(\vec{x})$ as

$$\vec{F} = \begin{bmatrix} G_2 \\ H_2 \\ G_3 \\ H_3 \\ \vdots \\ \vdots \\ G_M \\ H_M \\ G_{M+1} \\ H_{M+1} \end{bmatrix}, \quad (A.16)$$

where the G_i and H_i represent the components that arise primarily from the discretization of the horizontal momentum and energy equations, respectively, about the grid point (r_i, y_j) . The specific forms of the G_i and H_i are derived shortly. As mentioned above (p. 82), centered differencing results in each G_i and H_i involving at most six of the $2M$ $u_{i,j}$ and $T_{i,j}$. The Jacobian matrix derivatives of

$$\vec{G}(\vec{u}, \vec{T}) = \begin{bmatrix} G_2 \\ G_3 \\ \vdots \\ \vdots \\ G_M \\ G_{M+1} \end{bmatrix} \quad \text{and} \quad \vec{H}(\vec{u}, \vec{T}) = \begin{bmatrix} H_2 \\ H_3 \\ \vdots \\ \vdots \\ H_M \\ H_{M+1} \end{bmatrix} \quad (A.17)$$

with respect to \vec{u} and \vec{T} thus have the following sparse, banded forms:

$$\frac{\partial \vec{G}}{\partial \vec{u}} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & & & & & & & 0 \\ \alpha_{20} & \alpha_{21} & \alpha_{22} & & & & & & \\ \alpha_{30} & \alpha_{31} & \alpha_{32} & & & & & & \\ & & & \alpha_{M-2,0} & \alpha_{M-2,1} & \alpha_{M-2,2} & & & \\ & & & & \alpha_{M-1,0} & \alpha_{M-1,1} & \alpha_{M-1,2} & & \\ & & & & & \alpha_{M,0} & \alpha_{M,1} & & \\ 0 & & & & & & & & \end{bmatrix},$$

(A.18a)

$$\frac{\partial \vec{G}}{\partial \vec{f}} = \begin{bmatrix} \beta_{11} & \beta_{12} & & & & & & & 0 \\ \beta_{20} & \beta_{21} & \beta_{22} & & & & & & \\ \beta_{30} & \beta_{31} & \beta_{32} & & & & & & \\ & & & \beta_{M-2,0} & \beta_{M-2,1} & \beta_{M-2,2} & & & \\ & & & & \beta_{M-1,0} & \beta_{M-1,1} & \beta_{M-1,2} & & \\ & & & & & \beta_{M,0} & \beta_{M,1} & & \\ 0 & & & & & & & & \end{bmatrix},$$

(A.18b)

$$\frac{\partial \vec{H}}{\partial \vec{u}} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & & & & & & 0 \\ \gamma_{20} & \gamma_{21} & \gamma_{22} & & & & & \\ & \gamma_{30} & \gamma_{31} & \gamma_{32} & & & & \\ & & & & \gamma_{M-2,0} & \gamma_{M-2,1} & \gamma_{M-2,2} & \\ & & & & & \gamma_{M-1,0} & \gamma_{M-1,1} & \gamma_{M-1,2} \\ & & & & & & \gamma_{M,0} & \gamma_{M,1} \\ 0 & & & & & & & \end{bmatrix},$$

(A.18c)

$$\frac{\partial \vec{H}}{\partial \vec{T}} = \begin{bmatrix} \delta_{11} & \delta_{12} & & & & & & 0 \\ \delta_{20} & \delta_{21} & \delta_{22} & & & & & \\ & \delta_{30} & \delta_{31} & \delta_{32} & & & & \\ & & & & \delta_{M-2,0} & \delta_{M-2,1} & \delta_{M-2,2} & \\ & & & & & \delta_{M-1,0} & \delta_{M-1,1} & \delta_{M-1,2} \\ & & & & & & \delta_{M,0} & \delta_{M,1} \\ 0 & & & & & & & \end{bmatrix}.$$

(A.18d)

From Eqs. (A.10) and (A.15) through (A.18), the $J = \partial \vec{F} / \partial \vec{x}$ Jacobian is then easily computed from the nonzero elements in the Jacobians of Eqs. (A.13) as

(A.19)

DIFFERENCE EQUATIONS AND JACOBIAN ELEMENTS

Specific forms for \vec{G} and \vec{H} , and hence for \vec{F} and the various α , β , γ , and δ coefficients in Eqs. (A.18) and (A.19), are derived as follows. Subject to Eqs. (A.11), the first two lines of Eqs. (A.7) are approximated at $r = r_i$, $2 \leq i \leq M$, by

$$\begin{aligned}
 \frac{u_{i,1}}{T_{i,1}} \left(\frac{u_{i+1,1} - u_{i-1,1}}{2 \Delta r} \right) &= - \left(\frac{P_{i+1,1} - P_{i-1,1}}{2 \Delta r} \right) \\
 &+ M_1 \left(\frac{u_{i+1,1} - 2u_{i,1} + u_{i-1,1}}{(\Delta r)^2} \right) \\
 &+ \frac{1}{r_i} \left(\frac{u_{i+1,1} - u_{i-1,1}}{2 \Delta r} \right) - \frac{u_{i,1}}{r_i^2} \Bigg) , \\
 \frac{u_{i,1}}{T_{i,1}} \left(\frac{T_{i+1,1} - T_{i-1,1}}{2 \Delta r} \right) &= q(r_i, 0) - \sigma(T_{i,1}^4 - 1) \\
 &+ K_1 \left(\frac{T_{i+1,1} - 2T_{i,1} + T_{i-1,1}}{(\Delta r)^2} \right) \\
 &+ \frac{1}{r_i} \left(\frac{T_{i+1,1} - T_{i-1,1}}{2 \Delta r} \right) \Bigg) . \quad (A.20)
 \end{aligned}$$

From Eqs. (A.2b), (A.2d), and (A.12), we then also have

$$u_{1,1} = 0 , \quad T_{1,1} = T_{2,1} , \quad (A.21)$$

and

$$\begin{aligned}
 M_1 \left(\frac{u_{M+1,1} - u_{M,1}}{\Delta r} \right) &= \left(\frac{u_{M+1,1}}{T_{M+1,1}} \right)^2 (T_{M+1,1} - 1) + P_{M+1,1} , \\
 K_1 \left(\frac{T_{M+1,1} - T_{M,1}}{\Delta r} \right) &= \frac{u_{M+1,1}}{T_{M+1,1}} (T_{M+1,1} - 1) . \quad (A.22)
 \end{aligned}$$

For $j = 1$, we thus have

$$\begin{aligned}
 G_2 &= \frac{M_1}{\Delta r} (u_{3,1} - 2u_{2,1}) - \frac{1}{2} \left(\frac{u_{2,1}}{T_{2,1}} - \frac{M_1}{r_2} \right) u_{3,1} - \frac{1}{2} (p_{3,1} - p_{1,1}) \\
 &\quad - \left(\frac{M_1}{r_2} \right) u_{2,1} \Delta r, \\
 H_2 &= \frac{K_1}{\Delta r} (T_{3,1} - T_{2,1}) - \frac{1}{2} \left(\frac{u_{2,1}}{T_{2,1}} - \frac{K_1}{r_2} \right) (T_{3,1} - T_{2,1}) \\
 &\quad + \left(q(r_2, 0) - \sigma(T_{2,1}^4 - 1) \right) \Delta r; \tag{A.23}
 \end{aligned}$$

$$\begin{aligned}
 G_i &= \frac{M_1}{\Delta r} (u_{i+1,1} - 2u_{i,1} + u_{i-1,1}) - \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} - \frac{M_1}{r_i} \right) (u_{i+1,1} - u_{i-1,1}) \\
 &\quad - \frac{1}{2} (p_{i+1,1} - p_{i-1,1}) - M_1 \left(\frac{u_{i,1}}{r_i} \right) \frac{\Delta r}{r_i}, \\
 H_i &= \frac{K_1}{\Delta r} (T_{i+1,1} - 2T_{i,1} + T_{i-1,1}) - \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} - \frac{K_1}{r_i} \right) (T_{i+1,1} - T_{i-1,1}) \\
 &\quad + \left(q(r_i, 0) - \sigma(T_{i,1}^4 - 1) \right) \Delta r \tag{A.24}
 \end{aligned}$$

for $3 \leq i \leq M$; and

$$G_{M+1} = \frac{M_1}{\Delta r} (u_{M+1,1} - u_{M,1}) - \left(\frac{u_{M+1,1}}{T_{M+1,1}} \right)^2 (T_{M+1,1} - 1) - p_{M+1,1},$$

$$H_{M+1} = \frac{K_1}{\Delta r} (T_{M+1,1} - T_{M,1}) - \frac{u_{M+1,1}}{T_{M+1,1}} (T_{M+1,1} - 1) . \quad (A.25)$$

From Eqs. (A.23) through (A.25), the Jacobian elements in Eqs. (A.18) and (A.19) are then found to be

$$\alpha_{11} = -3 \left(\frac{M_1}{\Delta r} \right) - \frac{1}{2} \left(\frac{u_{3,1}}{T_{2,1}} \right) ,$$

$$\alpha_{12} = \frac{3}{2} \left(\frac{M_1}{\Delta r} \right) - \frac{1}{2} \left(\frac{u_{2,1}}{T_{2,1}} \right) ,$$

$$\beta_{11} = \frac{1}{2} \left(\frac{u_{2,1} u_{3,1}}{T_{2,1}^2} \right) ,$$

$$\beta_{12} = 0 ,$$

$$\gamma_{11} = -\frac{1}{2} \left(\frac{T_{3,1}}{T_{2,1}} - 1 \right) ,$$

$$\gamma_{12} = 0 ,$$

$$\delta_{11} = -\frac{3}{2} \left(\frac{K_1}{\Delta r} \right) + \frac{1}{2} \left(\frac{u_{2,1} T_{3,1}}{T_{2,1}^2} \right) - 4\sigma T_{2,1}^3 (\Delta r) ,$$

$$\delta_{12} = \frac{3}{2} \left(\frac{K_1}{\Delta r} \right) - \frac{1}{2} \left(\frac{u_{2,1}}{T_{2,1}} \right) ; \quad (A.26)$$

$$\alpha_{i-1,0} = \frac{M_1}{\Delta r} \left(1 - \frac{\Delta r}{2r_i} \right) + \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} \right) ,$$

$$\alpha_{i-1,1} = - \frac{M_1}{\Delta r} \left(2 + \left(\frac{\Delta r}{r_i} \right)^2 \right) - \frac{1}{2} \left(\frac{u_{i+1,1} - u_{i-1,1}}{T_{i,1}} \right) ,$$

$$\alpha_{i-1,2} = \frac{M_1}{\Delta r} \left(1 + \frac{\Delta r}{2r_i} \right) - \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} \right) ,$$

$$\beta_{i-1,0} = 0 ,$$

$$\beta_{i-1,1} = \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}^2} \right) (u_{i+1,1} - u_{i-1,1}) ,$$

$$\beta_{i-1,2} = 0 ,$$

$$\gamma_{i-1,0} = 0 ,$$

$$\gamma_{i-1,1} = - \frac{1}{2} \left(\frac{T_{i+1,1} - T_{i-1,1}}{T_{i,1}} \right) ,$$

$$\gamma_{i-1,2} = 0 ,$$

$$\delta_{i-1,0} = \frac{K_1}{\Delta r} \left(1 - \frac{\Delta r}{2r_i} \right) + \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} \right) ,$$

$$\delta_{i-1,1} = - 2 \left(\frac{K_1}{\Delta r} \right) + \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}^2} \right) (T_{i+1,1} - T_{i-1,1}) - 4\sigma T_{i,1}^3 (\Delta r) ,$$

$$\delta_{i-1,2} = \frac{K_1}{\Delta r} \left(1 + \frac{\Delta r}{2r_i} \right) - \frac{1}{2} \left(\frac{u_{i,1}}{T_{i,1}} \right) \quad (A.27)$$

for $3 \leq i \leq M$; and

$$\alpha_{M,0} = -\frac{M_1}{\Delta r} ,$$

$$\alpha_{M,1} = \frac{M_1}{\Delta r} - 2 \left(\frac{u_{M+1,1}}{T_{M+1,1}} \right) \left(1 - \frac{1}{T_{M+1,1}} \right) ,$$

$$\beta_{M,0} = 0 ,$$

$$\beta_{M,1} = \left(\frac{u_{M+1,1}}{T_{M+1,1}} \right)^2 \left(1 - \frac{2}{T_{M+1,1}} \right) ,$$

$$\gamma_{M,0} = -1 + \frac{1}{T_{M+1,1}} ,$$

$$\gamma_{M,1} = 0 ,$$

$$\delta_{M,0} = -\frac{K_1}{\Delta r} ,$$

$$\delta_{M,1} = \frac{K_1}{\Delta r} - \frac{u_{M+1,1}}{T_{M+1,1}^2} . \quad (A.28)$$

For $j \geq 2$, the derivation of relevant forms for \vec{G} and \vec{H} begins with a preliminary rewriting of Eqs. (A.1) in the following equivalent form:

$$\frac{1}{r} \frac{\partial}{\partial r} (r \rho u) + \frac{\partial}{\partial y} (\rho v) = 0 ,$$

$$\frac{1}{r} \frac{\partial}{\partial r} (r \rho u^2) + \frac{\partial p}{\partial r} + \frac{\partial}{\partial y} (\rho u v) = M_1 \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} \right) ,$$

$$\frac{\partial P}{\partial y} + \Delta p = 0 ,$$

$$\frac{1}{r} \frac{\partial}{\partial r} (ru) + \frac{\partial v}{\partial y} \equiv \frac{1}{r} \frac{\partial}{\partial r} (r\rho uT) + \frac{\partial}{\partial y} (\rho vT) = K_1 \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$

$$+ q(r, y) - \sigma(T^4 - 1) ,$$

$$\rho T = 1 .$$

(A.29)

Subject to Eqs. (A.13), this set is approximated at each interior grid point (r_i, y_j) , $2 \leq i \leq M$, of line j , $2 \leq j \leq N + 1$ by the finite difference system

$$\begin{aligned} \frac{1}{4 \Delta r} \left\{ \frac{r_{i+1}}{r_i} \left(\left(\frac{u}{T} \right)_{i+1,j} + \left(\frac{u}{T} \right)_{i+1,j-1} \right) - \frac{r_{i-1}}{r_i} \left(\left(\frac{u}{T} \right)_{i-1,j} + \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\} \\ + \frac{1}{\Delta y} \left(\left(\frac{v}{T} \right)_{i,j} - \left(\frac{v}{T} \right)_{i,j-1} \right) = 0 , \end{aligned} \quad (A.30a)$$

$$\begin{aligned} \frac{1}{4 \Delta r} \left\{ \frac{r_{i+1}}{r_i} \left(\left(\frac{u^2}{T} \right)_{i+1,j} + \left(\frac{u^2}{T} \right)_{i+1,j-1} \right) - \frac{r_{i-1}}{r_i} \left(\left(\frac{u^2}{T} \right)_{i-1,j} + \left(\frac{u^2}{T} \right)_{i-1,j-1} \right) \right\} \\ + \frac{1}{4 \Delta r} (P_{i+1,j} + P_{i+1,j-1} - P_{i-1,j} - P_{i-1,j-1}) \\ + \frac{1}{\Delta y} \left(\left(\frac{uv}{T} \right)_{i,j} - \left(\frac{uv}{T} \right)_{i,j-1} \right) \\ = M_1 \left(\frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j} + u_{i+1,j-1} - 2u_{i,j-1} + u_{i-1,j-1}}{2(\Delta r)^2} \right. \\ + \frac{1}{r_i} \left(\frac{u_{i+1,j} - u_{i-1,j} + u_{i+1,j-1} - u_{i-1,j-1}}{4 \Delta r} \right) \\ \left. - \frac{u_{i,j} + u_{i,j-1}}{2r_i^2} \right) , \end{aligned} \quad (A.30b)$$

$$\frac{1}{\Delta y} (P_{i,j} - P_{i,j-1}) = -\frac{A}{2} \left(\left(\frac{1}{T} \right)_{i,j} + \left(\frac{1}{T} \right)_{i,j-1} \right), \quad (\text{A.30c})$$

$$\begin{aligned} & \frac{1}{4 \Delta r} \left(\frac{r_{i+1}}{r_i} (u_{i+1,j} + u_{i+1,j-1}) - \frac{r_{i-1}}{r_i} (u_{i-1,j} + u_{i-1,j-1}) \right) \\ & + \frac{1}{\Delta y} (v_{i,j} - v_{i,j-1}) \\ & = K_1 \left(\frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j} + T_{i+1,j-1} - 2T_{i,j-1} + T_{i-1,j-1}}{2(\Delta r)^2} \right. \\ & \quad \left. + \frac{1}{r_i} \left(\frac{T_{i+1,j} - T_{i-1,j} + T_{i+1,j-1} - T_{i-1,j-1}}{4 \Delta r} \right) \right) \\ & \quad + \frac{1}{2} (q(r_i, y_j) + q(r_i, y_{j-1})) + \sigma \left(\left(\frac{T_{i,j} + T_{i,j-1}}{2} \right)^4 - 1 \right), \end{aligned} \quad (\text{A.30d})$$

ρ having been eliminated for convenience. This system is simplified by solving Eqs. (A.30a) and (A.30c) for $v_{i,j}$ and $P_{i,j}$ in terms of the various u and T on line j and variables on line $j - 1$ as

$$\begin{aligned} v_{i,j} &= \left(\frac{v}{T} \right)_{i,j-1} T_{i,j} - \frac{1}{4} \left(\frac{\Delta y}{\Delta r} \right) \left\{ \frac{r_{i+1}}{r_i} \left(\left(\frac{u}{T} \right)_{i+1,j} + \left(\frac{u}{T} \right)_{i+1,j-1} \right) \right. \\ & \quad \left. - \frac{r_{i-1}}{r_i} \left(\left(\frac{u}{T} \right)_{i-1,j} + \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\} T_{i,j}, \\ P_{i,j} &= P_{i,j-1} - \frac{A}{2} \left(\left(\frac{1}{T} \right)_{i,j} + \left(\frac{1}{T} \right)_{i,j-1} \right) \Delta y, \end{aligned} \quad (\text{A.31})$$

and substituting those results into Eqs. (A.30b) and (A.30d) to generate (for $2 \leq i \leq M$)

$$\begin{aligned}
 G_i \equiv & \frac{M_1}{2 \Delta r} (u_{i+1,j} - 2u_{i,j} + u_{i-1,j}) - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \left(\frac{u^2}{T} \right)_{i+1,j} - \frac{r_{i-1}}{r_i} \left(\frac{u^2}{T} \right)_{i-1,j} \right. \\
 & \left. - \frac{M_1}{r_i} (u_{i+1,j} - u_{i-1,j}) + 2 \left(\frac{M_1}{r_i^2} \right) u_{i,j} (\Delta r) - A \frac{\Delta y}{2} \left(\frac{1}{T_{i+1,j}} - \frac{1}{T_{i-1,j}} \right) \right) \\
 & - \left(\frac{\Delta r}{\Delta y} \right) u_{i,j} \left\{ \left(\frac{v}{T} \right)_{i,j-1} - \frac{\Delta y}{4 \Delta r} \left(\frac{r_{i+1}}{r_i} \left(\frac{u}{T} \right)_{i+1,j} - \frac{r_{i-1}}{r_i} \left(\frac{u}{T} \right)_{i-1,j} \right. \right. \\
 & \left. \left. + \frac{r_{i+1}}{r_i} \left(\frac{u}{T} \right)_{i+1,j-1} - \frac{r_{i-1}}{r_i} \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\} + R_i = 0 , \\
 H_i \equiv & \frac{K_1}{2 \Delta r} (T_{i+1,j} - 2T_{i,j} + T_{i-1,j}) - \frac{1}{4} \left(\left(\frac{r_{i+1}}{r_i} \right) u_{i+1,j} - \left(\frac{r_{i-1}}{r_i} \right) u_{i-1,j} \right. \\
 & \left. - \frac{K_1}{r_i} (T_{i+1,j} - T_{i-1,j}) \right) - \left(\frac{\Delta r}{\Delta y} \right) T_{i,j} \left\{ \left(\frac{v}{T} \right)_{i,j-1} - \frac{\Delta y}{4 \Delta r} \right. \\
 & \left. \times \left(\frac{r_{i+1}}{r_i} \left(\frac{u}{T} \right)_{i+1,j} - \frac{r_{i-1}}{r_i} \left(\frac{u}{T} \right)_{i-1,j} + \frac{r_{i+1}}{r_i} \left(\frac{u}{T} \right)_{i+1,j-1} - \frac{r_{i-1}}{r_i} \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\} \\
 & + \sigma \left(\left(\frac{T_{i,j} + T_{i,j-1}}{2} \right)^4 - 1 \right) \Delta r + \Pi_i = 0 , \tag{A.32}
 \end{aligned}$$

where

$$\begin{aligned}
 R_i = & \frac{M_1}{2 \Delta r} (u_{i+1,j-1} - 2u_{i,j-1} + u_{i-1,j-1}) - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \left(\frac{u^2}{T} \right)_{i+1,j-1} \right. \\
 & - \frac{r_{i-1}}{r_i} \left(\frac{u^2}{T} \right)_{i-1,j-1} - \frac{M_1}{r_i} (u_{i+1,j-1} - u_{i-1,j-1}) + 2 \left(\frac{M_1}{r_i^2} \right) u_{i,j-1} \Delta r \\
 & + 2(P_{i+1,j-1} - P_{i-1,j-1}) - A \frac{\Delta y}{2} \left(\frac{1}{T_{i+1,j-1}} - \frac{1}{T_{i-1,j-1}} \right) \\
 & + \frac{\Delta r}{\Delta y} \left(\frac{uv}{T} \right)_{i,j-1}, \\
 \Pi_i = & \frac{K_1}{2 \Delta r} (T_{i+1,j-1} - 2T_{i,j-1} + T_{i-1,j-1}) - \frac{1}{4} \left(\left(\frac{r_{i+1}}{r_i} \right) u_{i+1,j-1} \right. \\
 & - \left. \left(\frac{r_{i-1}}{r_i} \right) u_{i-1,j-1} - \frac{K_1}{r_i} (T_{i+1,j-1} - T_{i-1,j-1}) \right) + \frac{\Delta r}{\Delta y} v_{i,j-1} \\
 & + \frac{1}{2} \left(q(r_i, y_j) + q(r_i, y_{j-1}) \right) \Delta r.
 \end{aligned} \tag{A.33}$$

As outlined in Fig. A.4, a recursive Crank-Nicolson scheme is employed in subroutine MSWEEP to generate a numerical solution to Eqs. (A.1), (A.2a), (A.2b), and (A.2d), subject to a given $P(r, 0)$. For $j = 2, 3, \dots, N+1$, the solution on line j is found using solution data on line $j-1$, the solution for $j=1$ being used to start the recursion. For each $j \geq 2$, the relevant forms of G_i and H_i (as components of \vec{F}), $2 \leq i \leq M$, are therefore exactly those in Eqs. (A.32) [cf. Eqs. (A.24)], variables with $j-1$ suffices being known. From Eqs. (A.2b), (A.2d), and (A.14), we also have

$$u_{1,j} = 0, \quad T_{1,j} = T_{2,j}, \quad (A.34)$$

and

$$\begin{aligned} M_1 \left(\frac{u_{M+1,j} - u_{M,j} + u_{M+1,j-1} - u_{M,j-1}}{2 \Delta r} \right) &= \left(\frac{u_{M+1,j} + u_{M+1,j-1}}{T_{M+1,j} + T_{M+1,j-1}} \right)^2 \\ &\times \left(\frac{T_{M+1,j} + T_{M+1,j-1} - 2}{2} \right) \\ &+ \left(\frac{P_{M+1,j} + P_{M+1,j-1}}{2} \right. \\ &\left. + \frac{A}{2} (y_j + y_{j-1}) \right), \\ K_1 \left(\frac{T_{M+1,j} - T_{M,j} + T_{M+1,j-1} - T_{M,j-1}}{2 \Delta r} \right) &= \left(\frac{u_{M+1,j} + u_{M+1,j-1}}{T_{M+1,j} + T_{M+1,j-1}} \right) \\ &\times \left(\frac{T_{M+1,j} + T_{M+1,j-1} - 2}{2} \right). \end{aligned} \quad (A.35)$$

Therefore, for $j \geq 2$,

$$\begin{aligned} G_{M+1} &= \frac{M_1}{2 \Delta r} (u_{M+1,j} - u_{M,j} + u_{M+1,j-1} - u_{M,j-1}) - E_j^2 \left(\frac{T_{M+1,j} + T_{M+1,j-1} - 2}{2} \right) \\ &- P_{M+1,j-1} + \frac{A}{4} \left(\frac{1}{T_{M+1,j}} + \frac{1}{T_{M+1,j-1}} \right) \Delta y - \frac{A}{2} (y_j + y_{j-1}), \\ H_{M+1} &= \frac{K_1}{2 \Delta r} (T_{M+1,j} - T_{M,j} + T_{M+1,j-1} - T_{M,j-1}) \\ &- E_j \left(\frac{T_{M+1,j} + T_{M+1,j-1} - 2}{2} \right), \end{aligned} \quad (A.36)$$

where

$$E_j = \frac{u_{M+1,j} + u_{M+1,j-1}}{T_{M+1,j} + T_{M+1,j-1}} . \quad (A.37)$$

From Eqs. (A.32), (A.34), and (A.36), the Jacobian elements in Eqs. (A.18) and (A.19) are then as follows for each $j \geq 2$:

$$\begin{aligned} \alpha_{11} &= -\frac{3}{2} \left(\frac{M_1}{\Delta r} \right) - \left\{ \frac{\Delta r}{\Delta y} \left(\frac{v}{T} \right)_{2,j-1} - \frac{2}{4} \left(\left(\frac{u}{T} \right)_{3,j} + \left(\frac{u}{T} \right)_{3,j-1} \right) \right\} , \\ \alpha_{12} &= \frac{3}{4} \left(\frac{M_1}{\Delta r} \right) - \frac{2}{4} \left(2 \left(\frac{u}{T} \right)_{3,j} - \frac{u_{2,j}}{T_{3,j}} \right) , \\ \beta_{11} &= \frac{1}{4} \left(A \left(\frac{\Delta y}{2} \right) \left(\frac{1}{T_{2,j}} \right)^2 \right) , \\ \beta_{12} &= \frac{1}{4} \left(2 \left(\frac{u}{T} \right)_{3,j}^2 - A \left(\frac{\Delta y}{2} \right) \left(\frac{1}{T_{3,j}} \right)^2 - 2u_{2,j} \left(\frac{u}{T^2} \right)_{3,j} \right) , \\ \gamma_{11} &= 0 , \\ \gamma_{12} &= -\frac{2}{4} \left(1 - \frac{T_{2,j}}{T_{3,j}} \right) , \\ \delta_{11} &= -\frac{3}{4} \left(\frac{K_1}{\Delta r} \right) - \left\{ \frac{\Delta r}{\Delta y} \left(\frac{v}{T} \right)_{2,j-1} - \frac{2}{4} \left(\left(\frac{u}{T} \right)_{3,j} + \left(\frac{u}{T} \right)_{3,j-1} \right) \right\} \\ &\quad + 2\sigma \left(\frac{T_{2,j} + T_{2,j-1}}{2} \right)^3 \Delta r , \\ \delta_{12} &= \frac{3}{4} \left(\frac{K_1}{\Delta r} \right) - \frac{2}{4} \left(T_{2,j} \left(\frac{u}{T^2} \right)_{3,j} \right) ; \end{aligned} \quad (A.38)$$

$$\alpha_{i-1,0} = \frac{M_1}{2 \Delta r} \left(1 - \frac{\Delta r}{2r_i} \right) + \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(2 \left(\frac{u}{T} \right)_{i-1,j} - \frac{u_{i,j}}{T_{i-1,j}} \right),$$

$$\begin{aligned} \alpha_{i-1,1} = & - \frac{M_1}{2 \Delta r} \left(2 + \left(\frac{\Delta r}{r_i} \right)^2 \right) - \left\{ \frac{\Delta r}{\Delta y} \left(\frac{v}{T} \right)_{i,j-1} \right. \\ & - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(\left(\frac{u}{T} \right)_{i+1,j} + \left(\frac{u}{T} \right)_{i+1,j-1} \right) \\ & \left. + \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(\left(\frac{u}{T} \right)_{i-1,j} + \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\}, \end{aligned}$$

$$\alpha_{i-1,2} = \frac{M_1}{2 \Delta r} \left(1 + \frac{\Delta r}{2r_i} \right) - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(2 \left(\frac{u}{T} \right)_{i+1,j} - \frac{u_{i,j}}{T_{i+1,j}} \right),$$

$$\begin{aligned} \beta_{i-1,0} = & - \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(\frac{u}{T} \right)_{i-1,j}^2 - A \left(\frac{\Delta y}{2} \right) \left(\frac{1}{T_{i-1,j}} \right)^2 \\ & - \frac{r_{i-1}}{r_i} u_{i,j} \left(\frac{u}{T} \right)_{i-1,j} \Bigg), \end{aligned}$$

$$\beta_{i-1,1} = 0,$$

$$\begin{aligned} \beta_{i-1,2} = & \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(\frac{u}{T} \right)_{i+1,j}^2 - A \left(\frac{\Delta y}{2} \right) \left(\frac{1}{T_{i+1,j}} \right)^2 \\ & - \frac{r_{i+1}}{r_i} u_{i,j} \left(\frac{u}{T} \right)_{i+1,j} \Bigg), \end{aligned}$$

$$\gamma_{i-1,0} = \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(1 - \frac{T_{i,j}}{T_{i-1,j}} \right),$$

$$\gamma_{i-1,1} = 0,$$

$$\gamma_{i-1,2} = -\frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(1 - \frac{T_{i,j}}{T_{i+1,j}} \right),$$

$$\delta_{i-1,0} = \frac{K_1}{2 \Delta r} \left(1 - \frac{\Delta r}{2r_i} \right) + \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(T_{i,j} \left(\frac{u}{T^2} \right)_{i-1,j} \right),$$

$$\begin{aligned} \delta_{i-1,1} = & -2 \left(\frac{K_1}{2 \Delta r} \right) - \left\{ \frac{\Delta r}{\Delta y} \left(\frac{v}{T} \right)_{i,j-1} - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(\left(\frac{u}{T} \right)_{i+1,j} + \left(\frac{u}{T} \right)_{i+1,j-1} \right) \right. \\ & \left. + \frac{1}{4} \left(\frac{r_{i-1}}{r_i} \right) \left(\left(\frac{u}{T} \right)_{i-1,j} + \left(\frac{u}{T} \right)_{i-1,j-1} \right) \right\} + 2\sigma \left(\frac{T_{i,j} + T_{i,j-1}}{2} \right)^3 \Delta r, \end{aligned}$$

$$\delta_{i-1,2} = \frac{K_1}{2 \Delta r} \left(1 + \frac{\Delta r}{2r_i} \right) - \frac{1}{4} \left(\frac{r_{i+1}}{r_i} \right) \left(T_{i,j} \left(\frac{u}{T^2} \right)_{i+1,j} \right) \quad (A.39)$$

for $3 \leq i \leq M$; and

$$\alpha_{M,0} = -\frac{M_1}{2 \Delta r},$$

$$\alpha_{M,1} = \frac{M_1}{2 \Delta r} - 2E_j \left(\frac{1}{2} - \frac{1}{T_{M+1,j} + T_{M+1,j-1}} \right),$$

$$\beta_{M,0} = 0,$$

$$\beta_{M,1} = E_j^2 \left(\frac{1}{2} - \frac{2}{T_{M+1,j} + T_{M+1,j-1}} \right) - \frac{A}{4} \left(\frac{1}{T_{M+1,j}^2} \right) \Delta y.$$

$$\gamma_{M,0} = 0 ,$$

$$\gamma_{M,1} = -\frac{1}{2} + \frac{1}{T_{M+1,j} + T_{M+1,j-1}} ,$$

$$\delta_{M,0} = -\frac{K_1}{2 \Delta r} ,$$

$$\delta_{M,1} = \frac{K_1}{2 \Delta r} - \frac{E_i}{T_{M+1,j} + T_{M+1,j-1}} . \quad (A.40)$$

The detailed specification of \vec{G} , \vec{H} , and $J (= \partial \vec{F} / \partial \vec{x})$ is now complete for all cases. The equation $J\vec{\delta} = -\vec{F}$ is solved for $\vec{\delta}$ using Gaussian elimination [Isaacson and Keller, 1966]. For efficiency, standard sparse-matrix methods are employed: only nonzero elements of J [see Eq. (A.19)] are stored, and operations involving zero elements are automatically omitted.

PROGRAM LISTING

FORTRAN listings of all parts of the computer code are now presented. Table A.2 lists the main program, and Tables A.3, A.4, and A.5 list the subroutines BCFUNC, SPRINT, and MSWEEP, respectively.

Table A.2
LISTING OF MAIN PROGRAM

LINE	STATEMENT	00/00/00	11/00/00	00/00/00	00/00/00
1	FORMAT=1000				
2	DATA=1000				
3	DATA=1000				
4	DATA=1000				
5	DATA=1000				
6	DATA=1000				
7	DATA=1000				
8	DATA=1000				
9	DATA=1000				
10	DATA=1000				
11	DATA=1000				
12	DATA=1000				
13	DATA=1000				
14	DATA=1000				
15	DATA=1000				
16	DATA=1000				
17	DATA=1000				
18	DATA=1000				
19	DATA=1000				
20	DATA=1000				
21	DATA=1000				
22	DATA=1000				
23	DATA=1000				
24	DATA=1000				
25	DATA=1000				
26	DATA=1000				
27	DATA=1000				
28	DATA=1000				
29	DATA=1000				
30	DATA=1000				
31	DATA=1000				
32	DATA=1000				
33	DATA=1000				
34	DATA=1000				
35	DATA=1000				
36	DATA=1000				
37	DATA=1000				
38	DATA=1000				
39	DATA=1000				
40	DATA=1000				
41	DATA=1000				
42	DATA=1000				
43	DATA=1000				
44	DATA=1000				
45	DATA=1000				
46	DATA=1000				
47	DATA=1000				
48	DATA=1000				
49	DATA=1000				
50	DATA=1000				
51	DATA=1000				
52	DATA=1000				
53	DATA=1000				
54	DATA=1000				
55	DATA=1000				
56	DATA=1000				
57	DATA=1000				

Table A.2--Continued

FORMAL VALUE	ALTERNATE SPECIFIED VALUES	STATUS	UNIT	DESCRIPTION	NO.
58 0005001	0005001				58
59 0005001	0005001				59
60 0005001	0005001				60
61 0005001	0005001				61
62 0005001	0005001				62
63 0005001	0005001				63
64 0005001	0005001				64
65 0005001	0005001				65
66 0005001	0005001				66
67 0005001	0005001				67
68 0005001	0005001				68
69 0005001	0005001				69
70 0005001	0005001				70
71 0005001	0005001				71
72 0005001	0005001				72
73 0005001	0005001				73
74 0005001	0005001				74
75 0005001	0005001				75
76 0005001	0005001				76
77 0005001	0005001				77
78 0005001	0005001				78
79 0005001	0005001				79
80 0005001	0005001				80
81 0005001	0005001				81
82 0005001	0005001				82
83 0005001	0005001				83
84 0005001	0005001				84
85 0005001	0005001				85
86 0005001	0005001				86
87 0005001	0005001				87
88 0005001	0005001				88
89 0005001	0005001				89
90 0005001	0005001				90
91 0005001	0005001				91
92 0005001	0005001				92
93 0005001	0005001				93
94 0005001	0005001				94
95 0005001	0005001				95
96 0005001	0005001				96
97 0005001	0005001				97
98 0005001	0005001				98
99 0005001	0005001				99
100 0005001	0005001				100
101 0005001	0005001				101
102 0005001	0005001				102
103 0005001	0005001				103
104 0005001	0005001				104
105 0005001	0005001				105
106 0005001	0005001				106
107 0005001	0005001				107
108 0005001	0005001				108
109 0005001	0005001				109
110 0005001	0005001				110
111 0005001	0005001				111
112 0005001	0005001				112
113 0005001	0005001				113
114 0005001	0005001				114

Table A.2--Continued

FORTRAN-VIIIC 908-00			09/20/63	11/20/63	04/63	17
FORTRAN VIIC LICENSED OPERATING SYSTEMS AS STATED IN FIGURE 1-0-0-06			000 501 000000 000000 000000 000000			17
115	00000001	CALL SPOT (100)				115
116						116
117	00000001	IF (PLOT) GO TO 117				117
118						118
119						119
120						120
121						121
122	00000001	GO TO 117				122
123	00000001	GO TO 117				123
124	00000001	GO TO 117				124
125	00000001	GO TO 117				125
126	00000001	GO TO 117				126
127	00000001	GO TO 117				127
128	00000001	GO TO 117				128
129	00000001	GO TO 117				129
130	00000001	GO TO 117				130
131	00000001	GO TO 117				131
132	00000001	GO TO 117				132
133	00000001	GO TO 117				133
134	00000001	GO TO 117				134
135	00000001	GO TO 117				135
136	00000001	GO TO 117				136
137	00000001	GO TO 117				137
138	00000001	GO TO 117				138
139	00000001	GO TO 117				139
140	00000001	GO TO 117				140
141	00000001	GO TO 117				141
142	00000001	GO TO 117				142
143	00000001	GO TO 117				143
144	00000001	GO TO 117				144
145	00000001	GO TO 117				145
146	00000001	GO TO 117				146
147	00000001	GO TO 117				147
148	00000001	GO TO 117				148
149	00000001	GO TO 117				149
150	00000001	GO TO 117				150
151	00000001	GO TO 117				151
152	00000001	GO TO 117				152
153	00000001	GO TO 117				153
154	00000001	GO TO 117				154
155	00000001	GO TO 117				155
156	00000001	GO TO 117				156
157	00000001	GO TO 117				157
158	00000001	GO TO 117				158
159	00000001	GO TO 117				159
160	00000001	GO TO 117				160
161	00000001	GO TO 117				161
162	00000001	GO TO 117				162
163	00000001	GO TO 117				163
164	00000001	GO TO 117				164
165	00000001	GO TO 117				165
166	00000001	GO TO 117				166
167	00000001	GO TO 117				167
168	00000001	GO TO 117				168
169	00000001	GO TO 117				169
170	00000001	GO TO 117				170
171	00000001	GO TO 117				171

Table A.3
LISTING OF SUBROUTINE BCFUNC

FORTRAN-77 LINE NO.	FORTRAN-77 STATEMENT	FORTRAN-77 STATEMENT	FORTRAN-77 STATEMENT	FORTRAN-77 STATEMENT	FORTRAN-77 STATEMENT
1	0000001	CONTINUE			200
2					201
3					202
4	0000004	CONTINUE			203
5					204
6					205
7					206
8					207
9					208
10					209
11					210
12					211
13	0000013	CONTINUE			212
14	0000014	CONTINUE			213
15	0000015	CONTINUE			214
16	0000016	CONTINUE			215
17	0000017	CONTINUE			216
18					217
19					218
20					219
21					220
22					221
23					222
24					223
25					224
26					225
27					226
28					227
29					228
30	0000030	CONTINUE			229
31	0000031	CONTINUE			230
32					231
33					232
34					233
35					234
36	0000036	CONTINUE			235
37					236
38	0000038	CONTINUE			237
39	0000039	CONTINUE			238
40	0000040	CONTINUE			239
41	0000041	CONTINUE			240
42	0000042	CONTINUE			241
43	0000043	CONTINUE			242
44					243
45					244
46					245
47					246
48					247
49					248
50	0000050	CONTINUE			249
51	0000051	CONTINUE			250
52	0000052	CONTINUE			251
53	0000053	CONTINUE			252
54	0000054	CONTINUE			253
55	0000055	CONTINUE			254
56	0000056	CONTINUE			255
57	0000057	CONTINUE			256

Table A.3--Continued

FORTRAN-VIOL 804-00		09/20/82 11:04:00 PAGE 2/	4
FORTRAN VIOL LICENSED RESTRICTED RIGHTS AS STATED IN LICENST L-0136		***, SEE DOCUMENTATION PACKAGE, 08-101M99.	
58 0002721	EM = EXP(-CC*X(1))		265
59 0002821	U(1,1) = -CC*(EP-FM)/(EP+FM)		266
60			267
61 0002901			268
62 0003001	PSIG=UN*0.25/SIGMA		269
63 0003101	XNIN=0.5		270
64 0003201			271
65 0003301	U(1,1)=A*PSIG*X(1)/XNIN		272
66 0003401	T(1,1)=1.0*PSIG		273
67 0003501	P(1,1)=A*PSIG*(1.0+BETA*UN*(1.0-X(1)**2))		274
68			275
69 0003601	BETA=AA/(B.*SIGMA)		276
70 0003701	U(1,1)=B*ETA*X(1)		277
71 0003801	T(1,1)=1.10		278
72 0003901	BALOSS=AA/(B.*SIGMA)		279
73 0004001	P(1,1)=B*LOSS		280
74			281
75 0004101	CONTINUE		282
76 0004201	GO TO 900		283
77			284
78 0004301	CONTINUE		285
79 0004401	READ (A) (U(I,1), I = 1, MP)		286
80 0004501	READ (A) (T(I,1), I = 1, MP)		287
81 0004601	READ (A) (P(I,1), I = 1, MP)		288
82 0004701	NO 177 1=1, MP		289
83 0004801	P(I,1)=P(I,1)-LOSS		290
84 0004901	CONTINUE		291
85 0005001	GO TO 900		292
86			293
87			294
88			295
89			296
90			297
91			298
92 0005101	CONTINUE		299
93 0005201	IF (JJ.EQ.1) TAVG=T(11,JJ)		300
94 0005301	JJ=JJ+1		301
95 0005401	IF (JJ.GE.2) TAVG=0.5*(T(11,JJ)+T(11,JJ+1))		302
96			303
97 0005501	QVAL=0.0-SIGMA*(TAVG**4-1.0)		304
98			305
99 0005601	IF (JJ.GT.1.0) QVAL=QVAL-Q0		306
100			307
101			308
102			309
103			310
104			311
105 0005701	CONTINUE		312
106 0005801	XNIN = XNIN		313
107 0005901	CNIN=0.0		314
108 0006001	FMIN=FM*EXP(-CNIN*(11))		315
109 0006101	IF (11).GT.1.0) XNIN=0.0		316
110 0006201	GO TO 900		317
111			318
112			319
113			320
114			321

Table A.3--Continued

FORTRAN-900 ADDRESS		FORTRAN-900 ADDRESS		FORTRAN-900 ADDRESS	
FORTRAN-900 ADDRESS		FORTRAN-900 ADDRESS		FORTRAN-900 ADDRESS	
115	0007001	C	0007001	0007001	0007001
116	0007002	END	0007002	0007002	0007002
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134	0007020	END	0007020	0007020	0007020
135	0007021	END	0007021	0007021	0007021
136	0007022	END	0007022	0007022	0007022
137	0007023	END	0007023	0007023	0007023
138	0007024	END	0007024	0007024	0007024
END OF PROGRAM					
STATEMENT NUMBER: 201 FOR STATEMENT: STATEMENT 201					
SINGLE PRECISION EQUATION OF SUBROUTINE FOR STATEMENT 201					

Table A.4

LISTING OF SUBROUTINE SPRINT

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FORTMAN-VIJD 004-00
FORTRAN VIJD: LIGATED ON STRAIGHT PLATES AT STATION 10. LIGANDS 1-0456
09/20/02 11:04:06 PAGE 17
*** SEE TOP OF TABLE PAGE 00, 00-101000.

1 000001 SUMMING FOR SUBROUTINE
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4 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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6 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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8 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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10 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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12 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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20 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
21
22 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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24 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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40 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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48 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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50 000001 F(0,0) = (F(0,0),S(0),S(0),F(0),F(0),S(0),F(0),S(0))
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57

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Table A.5--Continued

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50	0017801	GADVER/NOV															
51	0017821	GADVER/NOV															
52	0017841	C 001781, 0															
53	0017861	IF (1, 0, 0) THEN (1, 0, 0) ELSE (0, 0, 0)															
54	0017881	IF (1, 0, 0) THEN (1, 0, 0) ELSE (0, 0, 0)															
55	0017901	IF (1, 0, 0) THEN (1, 0, 0) ELSE (0, 0, 0)															
56	0017921	GADVER/NOV															
57	0017941	GADVER/NOV															
58	0018061	IF (1, 0, 0) THEN (1, 0, 0) ELSE (0, 0, 0)															
59	0018101	GADVER/NOV															
60	0018201	GADVER/NOV															
61	0018301	GADVER/NOV															
62	0018401	GADVER/NOV															
63	0018501	GADVER/NOV															
64	0018601	GADVER/NOV															
65	0018701	GADVER/NOV															
66	0018801	GADVER/NOV															
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68	0019001	GADVER/NOV															
69	0019101	GADVER/NOV															
70	0019201	GADVER/NOV															
71	0019301	GADVER/NOV															
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102	0022401	GADVER/NOV															
103	0022501	GADVER/NOV															
104	0022601	GADVER/NOV															
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112	0023401	GADVER/NOV															
113	0023501	GADVER/NOV															
114	0023601	GADVER/NOV															

Table A.5--Continued

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PORTMAN VIOL: CULFINDO DISTRICTED M08-00		09/20/02 11:00:00 PM		09/20/02 11:00:00 PM	
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ANALYSIS OF THE LARGE URBAN FIRE ENVIRONMENT
Part II. Parametric Analysis and Model City Simulations
Unclassified

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12340 Santa Monica Boulevard, Los Angeles, California 90025

PSR Report 1210, November 1982, 120 pp., Contract ERM-C-0747, Work Unit 2564E

This report considers the fire environment that would result from a megaton-yield nuclear weapon explosion. An analysis (developed in Part I) that treats the physics of the burning zone and the volume immediately above it (turning region) is used to predict the velocity, temperature, and pressure fields of large area fires.

A sensitivity study explores the influence of turbulence, radiation, fire size, and burning intensity on the mean temperature levels and velocity fields. The results show hurricane-force velocities developing as the fire size or burning rate is increased. A sample calculation illustrates the change in fire-wind velocities as the fire evolves over time.

Calculations of the burning region for three model urban areas show the influence of building density and urban sprawl on the resulting fire environment. An additional set of predictions accounts for reduction of the fire intensity by blast in the urban center. For the latter cases, the temperature distribution is changed markedly, though the magnitude of the induced fire winds is not appreciably reduced.

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Part II. Parametric Analysis and Model City Simulations

Summary

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Final Report
Contract EMW-C-0747, Work Unit 2564E

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National Preparedness Programs
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SUMMARY

This report considers the large-fire environment that would occur in an urban area subject to a nuclear weapon explosion. The effects of system parameters are explored in a sensitivity study, and results for three model cities are presented.

The examples are characterized by extensive areas simultaneously burning, strong buoyancy, and large temperature gradients. Several such fires occurred during World War II. Though those fires were dramatic in intensity and destructiveness, each involved a relatively small area. A nuclear weapon explosion could generate a far larger area fire and a more severe fire environment. This report is intended to define such large fires. The results should be applicable for damage evaluation, formulation of shelter requirements, and rescue planning.

The calculations are based on the theory developed in Part I of this report, which is applicable to the fire zone and the volume immediately above it (turning region). The effects of variable area heating, turbulence, strong buoyancy, large temperature changes, and radiation are treated. The induced fire winds and rapid temperature changes at the fire periphery are uniquely determined by the use of jump conditions. Simulations of the Hamburg firestorm and a large Flambeau fire agreed well with available data.

The parametric analysis considers a large area fire and the effects of fire size, heating rates, mixing coefficients, and hot gas/smoke radiation. The results show the influence of those variables on the induced fire winds, mean temperature, and pressure gradients. In general, an increase in either the fire size or heating rate raises the mean temperature levels and the induced fire-wind velocities. For the larger heat release rates or fire sizes, the attendant increases in mean temperature and velocity are limited by compressibility effects.

Fires such as may result from a megaton-yield explosion are analyzed for three model urban areas. Each city is characterized by

a high-density center, a surrounding belt of mixed residential/ industrial construction, and a lower density suburban belt. Each model city portrays a different degree of building density and urban sprawl. The results illustrate how a particular city geometry affects the velocity and temperature fields for a given fire. An additional series of computations considers reduction of the fire area by severe blast damage and debris formation. For those calculations, complete burning was allowed in an annular area, with the fire intensity significantly reduced in the center.

Finally, the model is employed to estimate the behavior of the velocity and temperature fields as a function of fire evolution. Those calculations may indicate the most appropriate periods for effecting rescue operations as well as provide an estimate of time-dependent shelter loadings.